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US Army Corps
of Engineers
Construction Engineering
Research Laboratory

USACERL Technical Report E-90/13
September 1990
FEAP: Diurnal Energy Storage System Demonstration

AD-A228 023

Ice-on-Coil Diurnal Ice Storage Cooling System for a Barracks/Office/Dining Hall Facility at Yuma Proving Ground, AZ

by
Chang W. Sohn
Gerald L. Cler
Robert J. Kedl

Diurnal storage cooling systems provide an effective means for reducing peak electric energy demand at Army installations. The U.S. Army Construction Engineering Research Laboratory (USACERL) demonstrated an ice-on-coil diurnal ice storage (DIS) cooling system at a barracks/office/dining facility at Yuma Proving Ground, AZ as part of the Facilities Engineering Applications Program (FEAP). This report documents design, construction, and operational performance of the system and provides a design reference for ice-on-coil DIS cooling systems.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE
September 1990

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE

Ice-on-Coil Diurnal Ice Storage Cooling System for a Barracks/Office/Dining Hall Facility at Yuma Proving Ground, AZ

5. FUNDING NUMBERS

FEAP EB-FF9

6. AUTHOR(S)

Chang W. Sohn
Gerald L. Cler
Robert J. Kedl

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Construction Engineering Research Laboratory (USACERL)
2902 Newmark Drive, PO Box 4005
Champaign, IL 61824-4005

8. PERFORMING ORGANIZATION REPORT NUMBER

TR E-90/13

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Engineering and Housing Support Center
ATTN: CEHSC-FU
Fort Belvoir, VA 22060

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Diurnal storage cooling systems provide an effective means for reducing peak electric energy demand at Army installations. The U.S. Army Construction Engineering Research Laboratory (USACERL) demonstrated an ice-on-coil diurnal ice storage (DIS) cooling system at a barracks/ office/dining facility at Yuma Proving Ground, AZ as part of the Facilities Engineering Applications Program (FEAP). This report documents design, construction, and operational performance of the system and provides a design reference for ice-on-coil DIS cooling systems.

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14. SUBJECT TERMS

Yuma Proving Ground
Diurnal ice storage
ice-on-coil
cooling

15. NUMBER OF PAGES
54

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

FOREWORD

This study was carried out for the U.S. Army Engineering and Housing Support Center (USAEHSC), under the Facilities Engineering Applications Program (FEAP), work unit EB-FF9, "Diurnal Energy Storage System Demonstration." The technical monitor was Mr. B. Wasserman, CEHSC-FU.

Appreciation is expressed to the Directorate of Engineering and Housing (DEH) staff at Yuma Proving Ground (YPG), AZ, formerly under Mr. Bruce Dobbs, for their support on this project. Contributions by Mr. Bob Callahan, formerly with the DEH, and Mr. Jack Nixon were essential to completing the construction on schedule and scheduling YPG power demand, respectively. Appreciation is also expressed to participating electric utilities; the Arizona Public Service (APS) for their incentive award through the Storage of Thermal Energy for the Peak (STEP) Program; and the Western Area Power Administration (WAPA) through the Conservation and Renewable Energy (C&RE) Cost-Shared Assistance Program for their partial support.

This work was performed by the Energy and Utility Systems Division (ES) of the U.S. Army Construction Engineering Research Laboratory (USACERL). Dr. Gilbert Williamson is Chief of USACERL-ES. Dr. Sohn and Mr. Cler are Principal Investigators at USACERL. Mr. Kedl is associated with the Oak Ridge National Laboratory (ORNL). The technical editor was Gloria J. Wienke, Information Management Office, USACERL.

COL Everett R. Thomas is Commander and Director of USACERL, and Dr. L.R. Shaffer is Technical Director.

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1 INTRODUCTION

Background

The U.S. Army Construction Engineering Research Laboratory (USACERL) has summarized available energy storage technologies appropriate for Army applications.[1] Among them, the storage of cold water or ice was identified as the most cost-effective technology. To prove the efficacy of the storage cooling systems, USACERL is demonstrating three generic diurnal ice storage (DIS) cooling systems as part of the Facilities Engineering Application Program (FEAP). An ice-in-tank DIS cooling system was demonstrated at Fort Stewart, GA in 1987.[2] An ice harvester system will be demonstrated at Fort Bliss, TX in 1990. This report discusses an ice-on-coil system that has operated at Yuma Proving Ground (YPG), AZ since October 1988.

In the commercial sector, storage cooling systems have been developing rapidly, with more than 2000 systems installed and operating by the end of 1989. The characteristics of Army facilities are much more favorable for storage cooling application than those of commercial facilities.[3] Within the Army, engineers from installations and districts are showing growing interest in storage cooling systems. The FEAP DIS demonstration is part of the effort to provide information on these systems.

Objectives

The primary objectives of this report are to (1) document design, construction, and operational performance of an ice-on-coil DIS cooling system for Building 506 at YPG and (2) provide a design reference on ice-on-coil DIS cooling systems for Army engineers.

Approach

USACERL performed a feasibility study of a DIS cooling system for Building 506, a barracks/ office/dining facility. Oak Ridge National Laboratory (ORNL) designed the system in cooperation with USACERL and YPG. A construction contract was awarded through YPG to AT Mechanical, Phoenix, AZ. The system performance data were collected by ORNL with assistance from YPG and analyzed by USACERL.

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[1] R.J. Kedl and C.W. Sohn, *Assessment of Energy Storage Technologies for Army Facilities*, Technical Report E-86/04/ ADA171513 (U.S. Army Construction Engineering Research Laboratory [USACERL], May 1986).

[2] C.W. Sohn and J.J. Tomlinson, *Design and Construction of an Ice-in-Tank Diurnal Ice Storage Cooling System for the PX Building at Fort Stewart, GA*, Technical Report E-88/07/ADA197925 (USACERL, July 1988); C.W. Sohn, G.L. Cler, and R.J. Kedl, *Performance of an Ice-in-Tank Diurnal Ice Storage Cooling System for the PX Building at Fort Stewart, GA*, Technical Report E-90/10/ADA224739 (USACERL, June 1990).

[3] C.W. Sohn, "Offpeak Cooling Systems for Army Facilities," *Proceedings of the 1989 USACE Electrical and Mechanical Conference* (1989) pp 159-167.

Scope

Although this system design is an example of a retrofit application of DIS cooling system and not a universal design guide for general storage cooling systems, the information should be useful to anyone interested in the general concepts of storage cooling technology.

This report is the final project report to the Arizona Public Service (APS) and to the Western Area Power Administration (WAPA), who partially supported this project through the Storage of Thermal Energy for the Peak (STEP) program and Conservation and Renewable Energy (C&RE) Cost-Shared Assistance program, respectively.

Mode of Technology Transfer

It is recommended that information on the system be summarized in a Technical Note on ice storage cooling systems. Technical reports discussing design, installation, operation, and performance of the system will serve as interim design guidance. At the end of the demonstration program of the three generic DIS cooling systems (ice-in-tank at Fort Stewart, GA; ice-on-coil at YPG; and ice harvester at Fort Bliss, TX), USACERL will develop design and operating instructions for inclusion in the appropriate Army criteria documents.

2 FEASIBILITY STUDIES

Site Characteristics

Building 506 at YPG is an ideal facility for economical implementation of DIS technology; it consists of a dining facility, offices, and two wings of barracks with a total floor area of 86,100 sq ft.* The facility is air-conditioned by a 209-ton water cooled, centrifugal chiller and an 80-ton air cooled, reciprocating chiller. The 80-ton unit is used to meet the light cooling load of the facility during the seasonal changeover periods. The 80-ton reciprocating chiller can be converted easily to an ice maker, thereby reducing the capital cost of installing a new ice maker for the cooling system.

Figure 1 shows the hourly electric demand profile of YPG for a typical summer day, with a relatively sharp peak around 1430 hours. Building 506 is not separately metered, therefore any reduction in its demand during the afternoon (i.e., 1200 to 1600 hours) would reduce the overall YPG demand.

YPG Electric Resources

YPG, located in Western Arizona, buys its electrical power from the WAPA. Hydropower is the principal component and is supplied by the Parker Davis Dam (PD) and the Colorado River Storage Project (CRSP) under a long-term contract for both electrical energy and capacity. Recently, however, growth in YPG's electrical power requirements and decreased availability of hydropower sources have forced YPG to purchase additional power from APS. Figures 2 and 3 show the monthly power and energy requirements for YPG and the supply. Note that YPG must purchase from APS significant capacity in the summer and significant energy in the winter. APS charges a premium price for the additional power. The 750-kilowatt (kW) block of power contracted from APS costs almost as much as 5.2 megawatts (MW) contracted from PD and CRSP and a portion of the hydropower can be withdrawn after a 2-year notice.

The economic response to this situation must be based on the existing APS contract and the cost of power to YPG. As stated earlier, the capacity initially contracted for between YPG and APS is 750 kW. The contract states that determination of kilowatts for billing purposes shall be the greatest of:

1. The highest scheduled kilowatts from the contractor during any 60-minute period of the current month, or

2. Eighty percent of the highest scheduled kilowatts during any 60 minute period of the 6 summer months (May through October) of the previous 12 months ending with the current month, or

3. Two-thirds of the contract capacity.

Based on this contract clause, YPG is required to pay for a minimum of 500 kW whether it is used or not. The contract also states that the monthly bill shall be the greater of:

1. The kilowatt-hours (kWh) scheduled in advance by YPG, or

2. A 50 percent load factor based on the kilowatts determined above.

This criterion means that for a billing month with 30 days, at least 180,000 kWh of energy must be paid for. The amount is 186,000 kWh for months with 31 days.

*A metric conversion table is included on p 35.

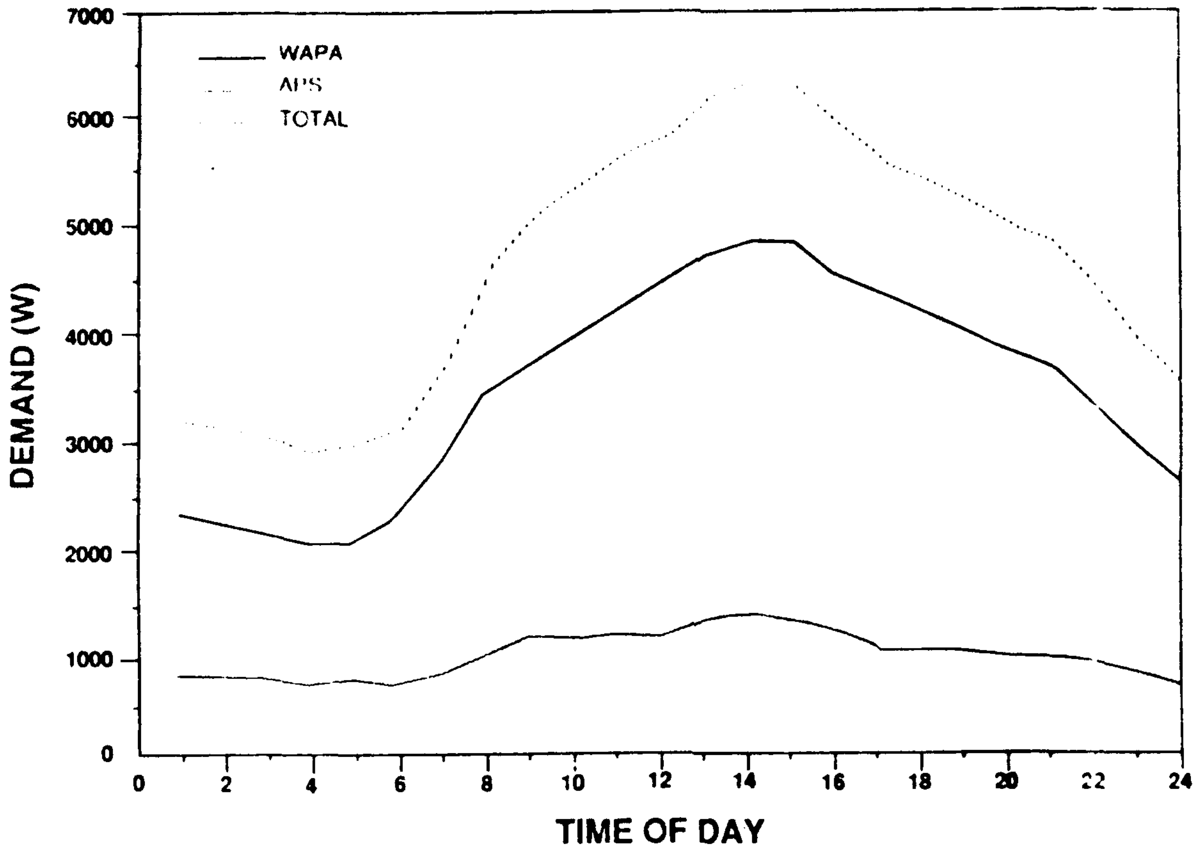


Figure 1. Typical YPG electrical demand.

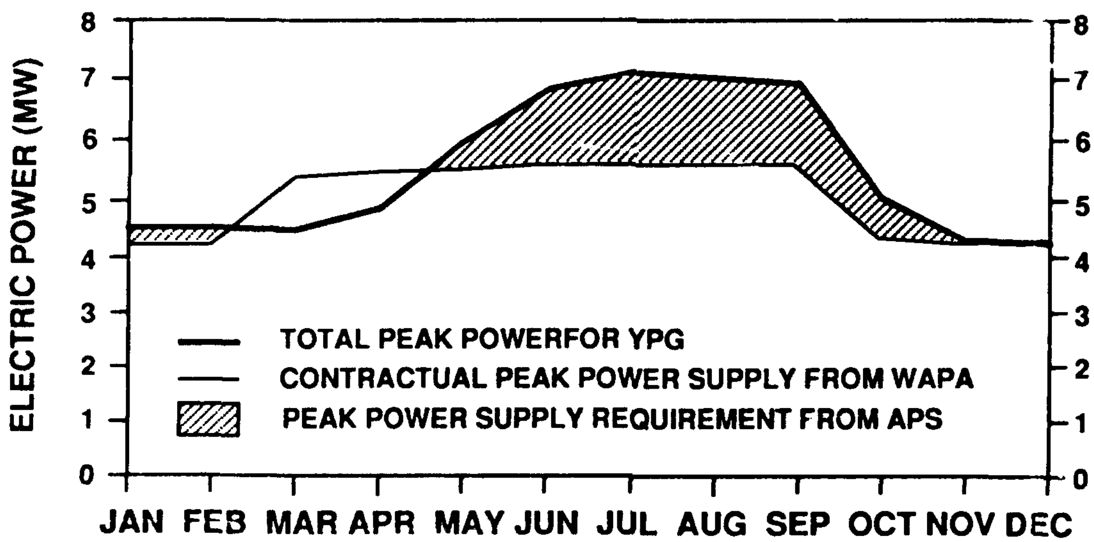


Figure 2. Total peak power load for YPG and contractual peak power supply from WAPA.

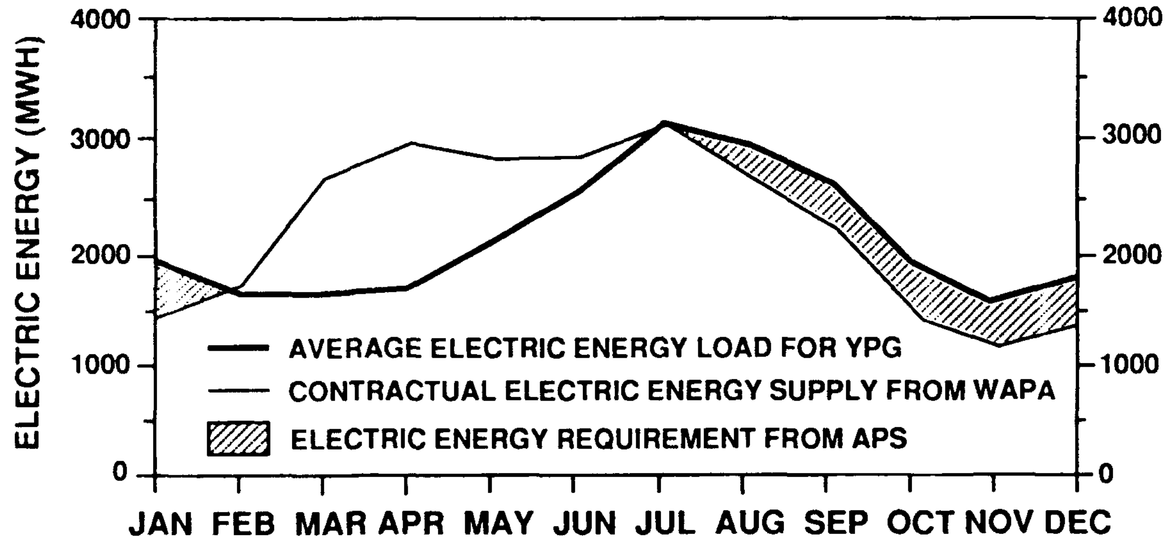


Figure 3. Total electric energy load for YPG and contractual electric energy supply from WAPA.

Since 500 kW and 180,000 kWh (186,000 kWh for 31-day months) are already paid for, YPG scheduled (as best it can) these levels of power and energy even though cheaper hydropower may be available from WAPA.

Anticipated Power Shifting With Cool Storage

The monthly capacity and energy requirements for YPG and contract amounts provided by PD and CRSP are shown in Table 1. Note that generally during the winter, there is a shortfall in energy and in the summer a shortfall in capacity. These shortfalls must be accommodated by APS under the terms of the existing contract. The numbers in parentheses in Table 1 represent a potential reduction in demand if a cool storage system was used to reduce summer peak demand by 200 kW.

To project cost savings to YPG through installation of a cool storage system capable of shifting 200 kW, it is assumed that:

1. Additional hydropower is not available from PD or CRSP, so that the PD/CRSP supply is limited to the contract power.

2. Contract power provided by APS complies with the terms of the APS contract stated earlier,

3. Additional power requirements are met by APS on an emergency basis.

In the past, APS has provided YPG with emergency power for months when high demands are expected. One such period was October 1983 when a 200-kW block of power was purchased (see Appendix A). For the present analysis, it is assumed that emergency power will be purchased under a similar agreement. Table 2 shows the cost of APS power (both contract and emergency) to meet the YPG monthly load. The APS rate schedule for contract power (an example of which is included in Appendix B) and the emergency power supplement (Appendix A) were used to determine the total costs of APS service for each month.

A similar approach was used to determine the cost of APS service with 200 kW displaced by a cool storage system operating from May through October. The costs are shown in Table 3. The difference between the totals in Tables 2 and 3 ($33,727) is the anticipated annual savings in electric utility costs for YPG with the DIS cooling system.

Table 1

Monthly Power and Energy Requirement of YPG

Month	Requirement*		PD/CRSP Supply**		Shortfall	
	MWh	kW	MWh	kW	MWh	kW
Jan	1920	4655	1450	4315	470	340
Feb	1670	4655	1750	4290	-	365
Mar	1685	4655	2665	5410	-	-
Apr	1740	5000	2965	5550	-	-
May	2140	6185 (5985)***	2825	5585	-	600 (400)
Jun	2575	7100 (6900)	2885	5705	-	1395 (1195)
Jul	3155	7400 (7200)	3155	5705	-	1695 (1495)
Aug	3000	7350 (7150)	2765	5705	235	1645 (1445)
Sep	2685	7300 (7100)	2310	5705	375	1595 (1395)
Oct	1995	5310 (5110)	1535	4360	460	950 (750)
Nov	1610	4400	1250	4285	360	115
Dec	1835	4400	1450	4315	385	85

*Data for 1984.

**Based on existing long-term contract.

***YPG demand with cool storage in Building 506.

Table 2

Cost of APS Service

Month	Contract APS Demand			Emergency Power*			Total
	MWh	kW	Cost($)	MWh	kW	Cost($)	Cost($)
Jan	470	500	25,180				25,180
Feb	180	500	12,710				12,710
Mar	180	500	12,710				12,710
Apr	180	500	12,710				12,710
May	216	600	15,029				15,029
Jun	270	750	18,508	232	645	22,372	40,880
Jul	270	750	18,508	340	945	32,778	51,286
Aug	270	750	18,508	322	895	31,044	49,552
Sep	270	750	18,508	304	845	29,309	47,817
Oct	388	750	23,879	72	200	6,937	30,816
Nov	360	500	20,903				20,903
Dec	385	500	22,041				22,041
							Total $341,634

*Cost of emergency power determined from YPG history: $17.08/kW; $.04511/kWh.

Table 3

Cost of APS Service After Installing Storage Cooling

Month	Contract APS Demand			Emergency Power*			Total
	MWh	kW	Cost($)	MWh	kW	Cost($)	Cost($)
Jan	470	500	25,180				25,180
Feb	180	500	12,710				12,710
Mar	180	500	12,710				12,710
Apr	180	500	12,710				12,710
May	180	500	12,710				12,710
Jun	270	750	18,508	166	445	15,435	38,943
Jul	270	750	18,508	268	745	25,841	44,349
Aug	270	750	18,508	250	695	24,107	42,615
Sep	270	750	18,508	232	645	22,372	40,880
Oct	460	750	27,156				27,156
Nov	360	500	20,903				20,903
Dec	385	500	22,041				22,041
							Total $307,907

* Cost of emergency power determined from YPG history: $17.08/kW; $.04511/kWh.

3 SYSTEM DESIGN

Description of Building 506

Building 506 (Figure 4) at YPG consists of two perpendicular wings separated by a small (6,400 sq ft) mess hall. The two wings are primarily barracks and offices. Each wing has three stories with floor area of 33,300 sq ft for Wing A and 46,400 sq ft for Wing B. Wing A, the older of the two, contains a 209-ton centrifugal chiller in the basement with a cooling tower located outside the building. Wing B is cooled by an 80-ton air cooled reciprocating chiller located outside the mechanical room. YPG personnel have found that the 80-ton unit provides redundant capacity, and the 209-ton unit in Wing A has sufficient capacity to cool the entire building. The chillers are interconnected so either one (or both) can supply cooling to the entire building. There is ample room adjacent to the 80-ton unit for an ice storage tank for DIS cooling.

Design Rationale

The design goal is to shift a portion of electric demand from the peak in the early afternoon hours caused by the air-conditioning load to nighttime when the demand is low. The first step in designing the DIS cooling system was to examine the 24-hour electric demand profile for YPG and define a window during which the 80-ton chiller could be turned off. A 4-hour window from 1200 to 1600 hours was selected to provide a sufficient margin to cover variations in the peaking hour.

A special consideration for designing the YPG DIS cooling system was the availability of two chillers. Although converting the 80-ton chiller into an ice maker could save the capital cost in system installation, a small air cooled reciprocating chiller is not the ideal equipment to make ice in view of the chiller's energy performance. This point will be examined in detail later in the performance analysis.

The next step was to determine the system design criteria incorporating the given capacity of the ice maker and the cooling requirement of the building. The criteria are:

1. The DIS system will be retrofitted as an "add-on" to the existing chilled water system so the building will be cooled by either the 209-ton centrifugal chiller or the DIS cooling system.

2. The existing 80-ton chiller will be converted into an ice maker. Some modifications to the chiller may be necessary.

3. An ice-on-coil type DIS cooling system will be designed.

4. The peak cooling requirement of the building was taken to be 209 tons. Although peak cooling load data for the individual building was not available, discussions with personnel from the YPG refrigeration shop revealed that the existing 209-ton chiller was sufficient to cool the entire building on the hottest day.

5. The design day conditions are from the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE).[4]

[4] *1985 Fundamentals Handbook* (American Society of Heating, Refrigerating, and Air Conditioning Engineers [ASHRAE], 1985).

Design dry bulb temperature = 111 °F
Average daily swing = 27 °F

Thus, design ambient temperature for the ice maker = 97.5 °F.

6. To reduce the peak, the 209-ton chiller would be turned off 4 hours a day, from 1200 to 1600 hours.

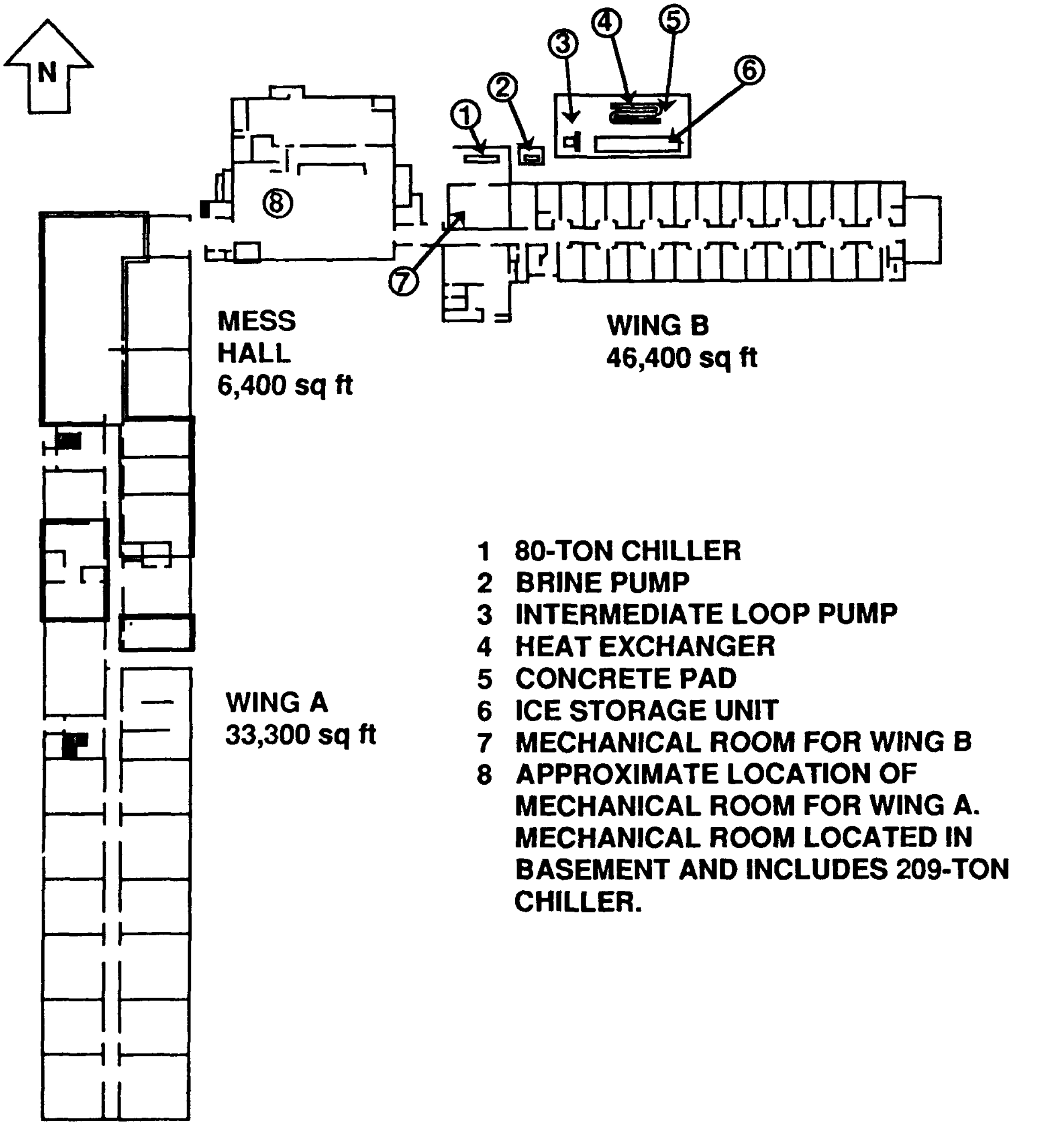


Figure 4. Plan view of Building 506 with layout of DIS equipment.

Ice Maker Sizing

The specifications for the existing 80-ton chiller are as follows:

Model: York Model LCHA-85-46C
Type: Liquid Chiller, Hermetic, Air Cooled
Nominal Capacity: 85 tons
Voltage Input: 460 Volt/3 Phase/60 Hz
Refrigerant: R-22
Chiller Operating Conditions:

	minimum	maximum
Leaving liquid temp:	40 °F	50 °F
Cooler water:	70 gallons per minute (gpm)	340 gpm
Air on condenser:	25 °F	115 °F

In the early stage of design, ORNL contacted the manufacturer of the 80-ton chiller to discuss the applicability of the chiller as an ice maker.[5] The 80-ton chiller will operate under ice making conditions with a brine leaving temperature of 25 °F. However, conversion to an ice maker will require:

1. Replacement or recalibration of capacity control system (Replaced),
2. Replacement or recalibration of freeze protection control (Recalibrated),
3. Replacement or recalibration of low pressure cutoff switch (Replaced),
4. Evaluation of wire sizing (Inspected and satisfactory),
5. Close attention to potential variations in flowrates for the brine pumping system.

Based on the information from the chiller manufacturer, the design discharge brine temperature from the ice maker was specified as 25 °F. The lower discharge temperature derates the capacity of the chiller. As predicted by the manufacturer, based on 25 °F discharge temperature, the capacity at 95 °F air temperature is 53 tons and the capacity at 105 °F air temperature is 50 tons. Interpolation for a design air temperature of 97.5 °F yields 52.2 tons. The design ice maker capacity was taken to be 85 percent of this value because (1) the manufacturer's data may apply only to laboratory environment operating conditions, (2) the existing chiller is over 10 years old, and (3) the expected ice making operating conditions lie beyond the chiller's normal design operating conditions as a chilled water maker. Therefore, the actual ice making capacity of the converted ice maker is 45 tons.

Ice Storage Sizing

The 80-ton chiller will make ice only during the offpeak period. The stored ice will then be used during the peak electric demand period to meet the cooling requirements of the building. As noted earlier, the cooling load of the building during the peak period will be taken to be 209 tons during the entire time cooling is supplied by melting ice. Table 4 relates the ice storage tank capacity to the charge and discharge times.

Table 4 shows that an 18-hour charge time is inadequate because the cooling capacity is less than required for either 4- or 6-hour discharge times. A 19-hour charge time results in a cooling capacity that is marginally adequate for a 4-hour discharge time but inadequate for a 5-hour discharge time. A 20-hour charge time results in a cooling capacity with a greater factor of safety and still allows a 4-hour discharge time. The 21-hour charge time leaves only a 3-hour discharge time and the cooling capacity is much greater than required. Thus, the 20-hour charge time and 4-hour discharge time seems the most appropriate cycle for this ice storage system. The capacity of the ice storage tank must be 900 ton-h or greater.

[5] Personal communication, York Air Conditioning, January 28, 1987.

Table 4

Ice Storage Tank Sizing Calculations

Charge time (in hours)	Stored ice (ton-h)	Discharge time (in hours)	Cooling capacity (ton)
18	810	6	135
18	810	4	202
19	855	5	171
19	855	4	214
20	900	4	225
21	945	3	315

Baltimore Aircoil (BAC) is one manufacturer of the ice-on-coil type of ice storage tank evaluated in this demonstration. The tank consists of multiple tube, serpentine coils submerged in an insulated tank of water. The system is charged by pumping low temperature brine through the tubes and freezing ice on the tube surface. When fully charged, the ice thickness around the tube is approximately 1.4 in. The system is discharged by pumping chilled water directly through the ice side of the tank. This cold water is supplied to the building chilled water system at approximately 32 °F and remains at this temperature until complete discharge of the storage tank. The water in the storage tank is agitated by bubbling air through it. This assures mixing and prevents stratification of return water during discharge. The capacity of the ice storage tank for this demonstration is near the largest storage tank supplied by BAC. They manufacture three tanks with capacities around 900 ton-h. Unfortunately, the recommended brine (30 percent ethylene glycol) flowrates for these three tanks are greater than the maximum allowable for the chiller (340 gpm). The next larger size storage tank has a storage capacity of 1050 ton-h, but the recommended brine flowrate is 270 gpm, which is within the recommended range for the chiller. The larger tank was used for this system.

System Schematics

A simplified schematic of the DIS cooling system for Building 506 is shown in Figure 5. The system consists of three recirculating loops; the brine loop, chilled water loop, and a heat exchanger loop between the ice storage tank and chilled water loop. The heat exchanger loop is needed to isolate the ice storage tank, which is open to the atmosphere, from the chilled water loop, which is a closed, pressurized loop.

Pumps

The existing chilled water pump has a capacity of 350 gpm. Because of the additional piping and the new heat exchanger, it was necessary to replace this pump with one having the same capacity but a higher head. The chilled water temperature difference (Δ T) at this flowrate, for a load of 209 tons, will be about 14 degrees.

The heat exchanger loop pump capacity was specified at 500 gpm. This value gives a Δ T of 10 degrees at the maximum load of 209 tons.

The brine pump is rated at 280 gpm, based on a recommendation by York Air Conditioning, when the chiller is used to make ice. A 30 percent glycol solution is specified for this system.

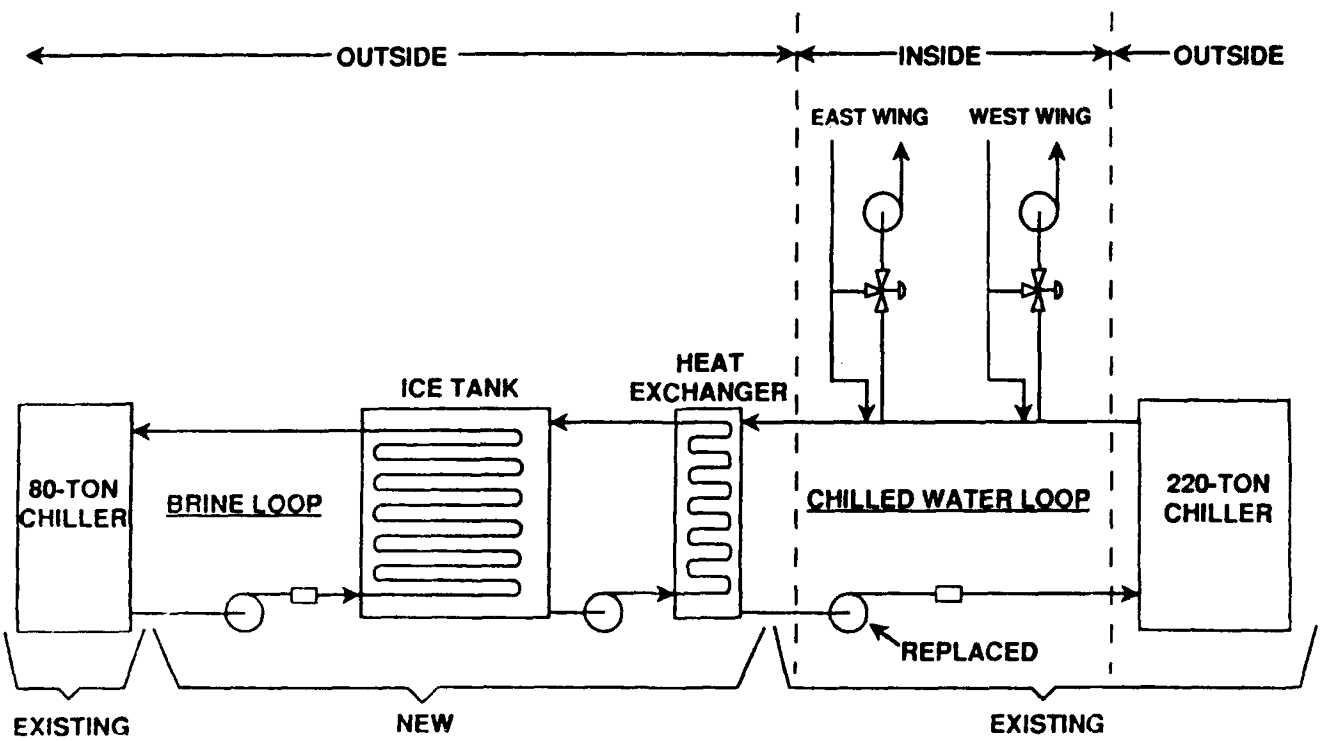


Figure 5. Schematic of DIS cooling system at YPG.

Heat Exchanger

The specifications for the heat exchanger are as follows:

	Temp in (°F)	Temp out (°F)	Flow (gpm)	Fluid
Shell	54	40	350	Building chilled water
Tube	35	45	500	Water from ice tank

Note that, although the original building chilled water system was designed for a supply temperature of 45 °F, 40 °F was specified for the new system to provide a margin of safety. The specific heat exchanger selected was a BAC Model 10-12-3-1A, which is an S-shaped, counter-current, shell-and-tube heat exchanger with copper tubes and a carbon steel shell.

Equipment Layout

The locations of major equipment for the DIS cooling system are shown in Figure 4. Sufficient space was available behind Wing B to locate the new equipment close to the 80-ton chiller and the mechanical room. However, a seldom used walkway had to be rerouted. Most of the new equipment is located on a single concrete pad; the brine pump is located on a separate pad.

Controls

Controls for the system are straightforward. A manual summer-winter switch activates the air-conditioning system in the summer and deactivates it in winter. One 7-day programmable electronic timer, with 24-hour battery backup, controls the operation of both chillers and the associated equipment. (Note that the timer must be adjusted when the installation changes between standard time and daylight savings time.) The ice tank is equipped with a manually adjustable ice thickness controller that controls the amount of ice manufactured (in 20 percent increments). This device gives the operator the option of making less ice during the intermediate seasons. The efficiency of the chiller is greater when the diurnal freezing and melting is carried out close to the tube surface rather than through an additional thickness of ice that remains frozen. Thus, it is cost effective to make the only amount of ice needed.

The mode of daily system operation is as follows:

16:00-12:00 (next day):	220-ton chiller cools Building 506. 80-ton chiller makes ice in the tank.
12:00-16:00:	Both chillers are off. Ice storage cools Building 506.

4 SYSTEM CONSTRUCTION

Construction Logistics

ORNL developed a bid package for installing the system in cooperation with USACERL and the Directorate of Engineering and Housing (DEH) staff at YPG. The original specifications required the contractor to provide all the equipment needed for the system, including a storage tank and a heat exchanger. Four quotes, each exceeding $200,000, were rejected due to a statutory spending limit on the allocated funds ($200,000 in Operation and Maintenance, Army [OMA] funds for minor construction) and a cost overrun. A revised bid package was prepared by separating equipment procurement by the Government and installation of the Government furnished equipment by the contractor. USACERL procured an ice storage tank and a heat exchanger. The YPG contract office awarded the installation contract to AT Mechanical, the lowest bidder. System installation was supervised by the DEH staff at YPG. USACERL managed the project execution from the funding stage to acceptance of the installed DIS cooling system by YPG. Figures 6, 7, and 8 show the site before, during, and after installation, respectively.

Project Chronology

01 Oct 86: project authorized.

18 Dec 86: Building 506, YPG selected; initial project conference at YPG.

10 Mar 87: ORNL draft design/bid specifications to YPG.

21 Apr 87: bid specifications completed; contracting process began.

06 Jul 87: four bids were opened at YPG (quotes were $268,507; $237,497; $223,469; and $221,800).

15 Jul 87: site conference. Bids were rejected on the basis of lack of certified funds and the $200,000 statutory spending limit on the type of allocated funds. A second round of bidding based on separating hardware procurement from system installation was initiated. The storage tank and heat exchanger were to be procured by USACERL.

05 Nov 87: revised draft bid package to YPG.

15 Dec 87: USACERL awarded hardware procurement contract to Roger L. Echelmeir Co. ($68,034).

02 Mar 88: storage tank and heat exchanger shipped from factory to YPG.

22 Mar 88: five bids were opened at YPG (quotes were $234,000; $179,281; $159,000; $135,679; and $114,435).

10 May 88: AT Mechanical, the lowest bidder, was awarded the installation contract ($114,435). Preconstruction conference at YPG; notice to proceed issued.

05 Aug 88: preliminary system performance testing completed.

25 Aug 88: formal acceptance of system by YPG. Onsite demonstration conducted for the Army.

Figure 6. Job site before construction.

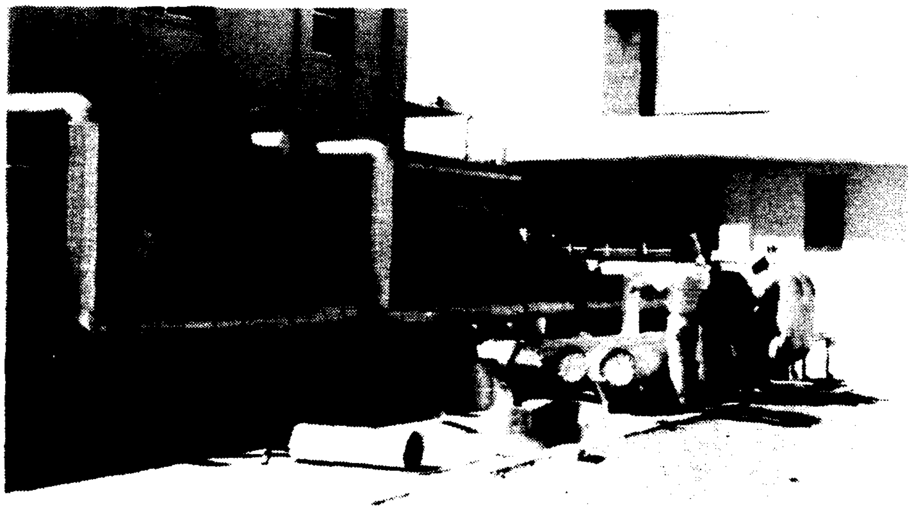


Figure 7. Job site during construction.

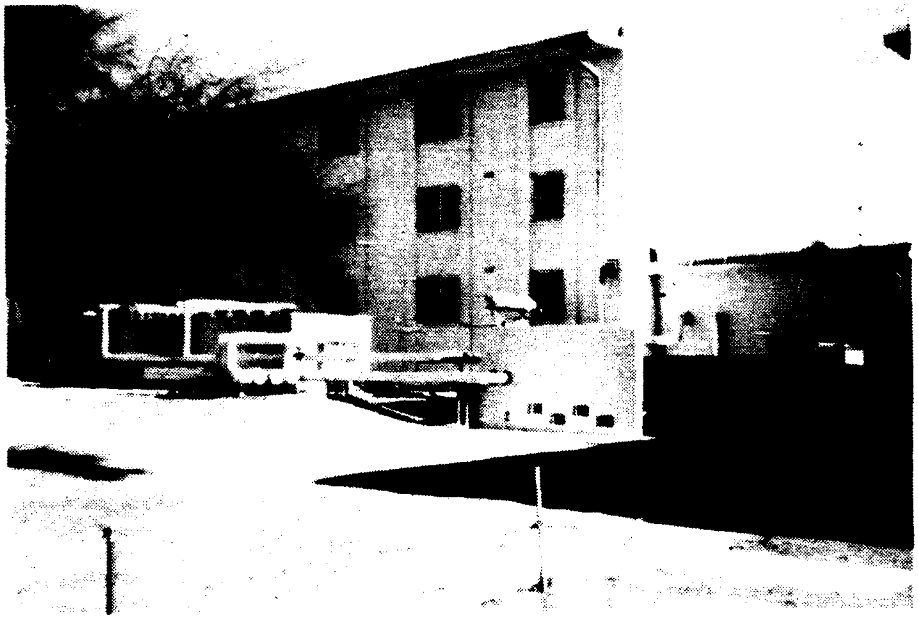


Figure 8. Completed DIS cooling system.

Problems Encountered and Lessons Learned

Construction Cost

During the early part of 1987, the job was advertised through the Commerce Business Daily (CBD) on a turnkey basis of specifications. The purpose of such an approach was to establish a single source of responsibility for parts and labor. As discussed in the previous section, the four quotes received were too far over the estimate to accept. A realistic cost of a retrofit storage cooling system is expected to be about \$150/ton-h.[6] For a 1050-ton-h capacity system, the expected cost estimate would be about \$157,500. The lowest bid received was \$221,800. Therefore, the quotes were rejected citing reasons discussed earlier.

In 1988, the job was advertised again with revised specifications that separated installation labor from equipment procurement. USACERL procured the ice storage tank and heat exchanger for \$60,198 and \$7836, respectively. Five installation quotes were received ranging from \$114,435 to \$234,000. The total equipment cost was \$68,034 and the labor cost \$114,435, with a total project cost at \$182,469. Postmortem cost studies of the three demonstration systems are in progress to identify the sources of cost escalation.[7]

[6] C.W. Sohn and G.L. Cler, *Market Potential of Storage Cooling Systems in the Army*, Technical Report E-89/13/ADA213977 (USACERL, September 1989).

[7] "Statement of Work, Independent Review of USACERL Field Demonstration of Diurnal Ice Storage Cooling Systems for Army Facilities," for Science Applications International Corporation (USACERL, 28 March 1989).

It should be noted that the second round of bidding resulted in a 20 percent reduction in total system cost (from $221,800, the lowest quote in the first round, to $182,469). It is natural that the reduced scope of system warranty would encourage a lower bid from the contractors. However, it is not clear yet that the higher bid was just to cover the extra warranty for the equipment. Even if the equipment was provided by the contractor, it must have been covered by the original manufacturer's warranty. The cause of a higher cost with a single source of responsibility is probably attributable to the contractors' uneasiness with the DIS cooling technology. Unfamiliarity rather than the complexity of the technology would probably be the cause of such a conservative cost estimate. With further dissemination of the storage cooling technology in the private sector as well as in the Army, more contractors would be exposed to the technology and their bids should be more competitive.

System Construction

During the period between the contract award and the issuance of notice to proceed, the main (209-ton) centrifugal chiller failed. Replacement was not included in the contract. YPG replaced the chiller with a new, high efficiency, 220-ton centrifugal chiller before the DIS system construction. The performance of the new chiller (220-ton unit) is presented in the next chapter.

During construction, the cooling service to Building 506 was not compromised; cooling was provided by the new 220-ton chiller. A temporary pipe was installed between the 220-ton chiller and the building chilled water supply main. A connection between the building chilled water loop and the ice tank/heat exchanger loop was made while the temporary piping supplied cooling to the building. After the connection was made, the temporary piping was removed, and the completed system began cooling the building.

Replacement of Air Blower

During the first few weeks of operation in August 1988, an air blower for the ice storage tank failed. The blower agitates the water inside the tank to achieve uniform freezing and melting of ice on the coil inside the tank. The manufacturer of the ice storage tank (BAC) provided a new blower (as covered by the warranty), and YPG personnel replaced it.

Replacement of Ice Maker Compressors

YPG formally accepted the system on 25 August 1988. After a few weeks of operation, the measurement of the ice maker output showed a significant decrease in ice production. Two of the four small compressors in the ice maker (80-ton reciprocating chiller) tested bad and were replaced.

5 SYSTEM PERFORMANCE

System Instrumentation

The performance of a DIS cooling system is based primarily on the system's ability to shift electrical demand from the peak period to offpeak. The system's energy performance based on the cooling delivered versus energy consumed also defines performance. This ratio of energy used over cooling output, the power consumption factor (PCF), is generally higher for a DIS system than for a conventional cooling system.

To analyze performance, the cooling system was instrumented with thermocouples, flowmeters, and watt/watt-hour meters. Data from this instrumentation was recorded at 15-minute intervals and stored on computer cassettes for later analysis. Figure 9 lists the instrumentation used to monitor the system and shows the location of each sensor. Temperatures were measured by type T (copper-constantan) thermocouples sheathed in 1/8-in. stainless steel tubing and inserted into the flow stream. Inside air temperature was measured in the return air duct of the air handling unit. The ambient air temperature was measured with a thermocouple shielded from direct sunlight by inserting it in a piece of PVC pipe equipped with a small fan to ensure a supply of fresh air. Flow rates were measured with vortex shedding type flow meters. These have no moving parts and once calibrated, they maintain good accuracy. The electric power and energy were measured with kW/kWh transducers and appropriate transformers. The signals from the 12 data channels were sent to a data logger (located onsite) and recorded on cassettes.

The cooling output from the two chillers can be calculated from the data collected. Cooling from the 220-ton chiller is used directly by Building 506 whereas cooling produced by the 80 ton chiller is stored in the ice storage tank to be used during the peak demand period of the day. When the stored ice is being used to cool the building, the recovered cooling is measured by the chilled water sensors. This allows the storage tank's efficiency to be determined. With this information, and the readings from watt/watt-hr meters, the PCF of the chillers was calculated along with the demand reduction capability of the DIS system. Calculation of these quantities are discussed in the next section.

Data Collection and Reduction

The data recorded by the data logger at YPG was sent to ORNL weekly where it was read from the cassettes and recorded on a floppy disk in a format readable by a BASIC computer program These disks were then sent to USACERL for analysis.

The cooling delivered by the two chillers and the ice tank (during the peak demand period) can be calculated by:

$$Q = \dot{m} \times C_p \times (T_r - T_s) \qquad \text{[Eq 1]}$$

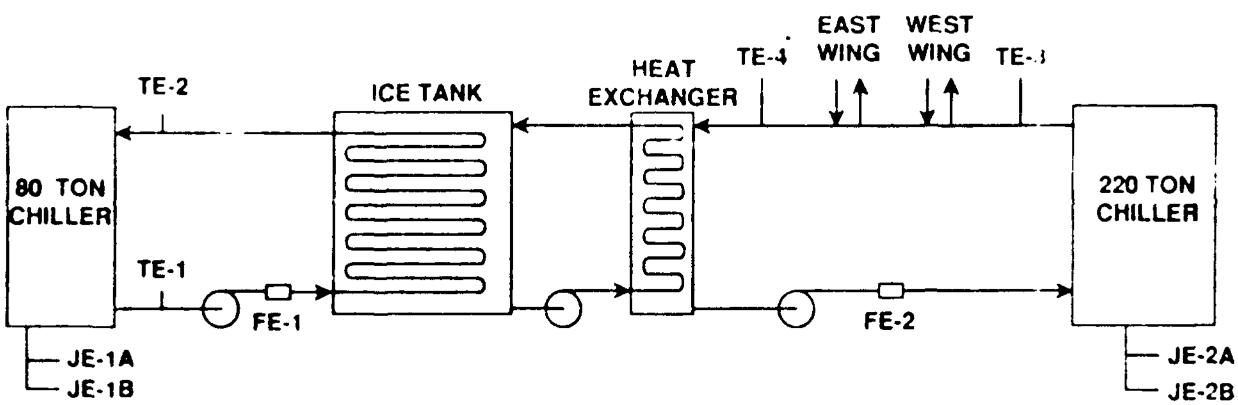
where Q = the rate of cooling delivered (tons),
$\dot{m}$ = the mass flowrate of the fluid (volume flowrate x density),
C_p = the specific heat of the fluid,
$(T_r - T_s)$ = the difference between the return and supply temperatures of the fluid.

Properties of the heat transfer media (specific heat and density of water and brine) are taken from the *1985 ASHRAE Fundamentals Handbook*. Since the data is measured in 15-minute intervals, Q is actually the average rate of cooling during the time period. During normal operation (after initial startup transients) the change in system operation is generally rather slow so the above calculation can be assumed to reflect the rate of cooling. The total cooling delivered (ton-hours) can be determined by summing the Qs from the 15-minute intervals over the time period of interest.

Electric power and energy are obtained directly from the data, again over 15-minute intervals. Calculation of the total energy consumed is done by summing the energy consumed in 15-minute intervals over the time period of interest. With this information, the system performance can be determined.

Energy Performance of the Cooling System

The 220-ton centrifugal chiller operates in a direct cooling mode in that all cooling generated is used immediately to cool the building. This chiller operates as required to meet the cooling demand for all hours of the day except from 1200 to 1600 hours. The 80-ton chiller is used to produce ice in the storage tank. It operates continuously from 1600 hours until the storage tank is fully charged or 1200 hours the following day. The performance of both chillers was monitored during the entire 1989 cooling season and is described below.



LABEL	DESCRIPTION
TE-1	BRINE SUPPLY TEMPERATURE TO ICE TANK
TE-2	BRINE RETURN TEMPERATURE FROM ICE TANK
TE-3	CHILLED WATER SUPPLY TEMPERATURE TO BUILDING
TE-4	CHILLED WATER RETURN TEMPERATURE FROM BUILDING
TE-5	OUTSIDE AIR TEMPERATURE
TE-6	INSIDE AIR TEMPERATURE
JE-1A	80-TON CHILLER DEMAND (KW)
JE-2A	220-TON CHILLER DEMAND (KW)
JE-1B	80-TON CHILLER ENERGY (KW-HR/15 MIN)
JE-2B	220-TON CHILLER ENERGY (KW-HR/15 MIN)
FE-1	BRINE FLOW RATE (GAL/15 MIN)
FE-2	CHILLED WATER FLOW RATE (GAL/15 MIN)

Figure 9. Instrumentation diagram.

Demand Shifting by the DIS Cooling System

The economic benefits for the user of a DIS cooling system result from the reduced demand portion of the facilities' electric bills. This goal was accomplished. Between 1600 hours and 1200 hours the following day, the DIS system stores ice to be used for cooling during the upcoming peak period, 1200 to 1600 hours. At 1200 hours, both chillers are turned off and the ice melts as required to meet the building's cooling load. The peak day operation of the ice making chiller is shown in Figure 10. This figure shows the demand reduction capability of the DIS cooling system during the peak demand setting period.

On 17 August 1989, the 220-ton chiller was running at a PCF of 0.8 kW/ton. During the peak window, Building 506 drew at the peak rate of 173 tons of cooling from the ice storage. Since the 220-ton chiller was off during the window, the ice storage should have reduced the electric demand by the chiller for cooling the building (R1) by,

$$R1 = 173 \text{ (ton)} \times 0.8 \text{ (kW/ton)}$$

$$= 138.4 \text{ (kW)}$$

Further reduction in electric demand resulted from turning off the cooling tower fan and pump for the 220-ton chiller. The pumping power requirement by the cooling tower condenser loop (R2) is.

$$R2 = 10 \text{ (hp)}$$

$$= 7.5 \text{ (kW)}$$

The power requirement for the cooling tower fan (R3) is,

$$R3 = 15 \text{ (hp)}$$

$$= 11.2 \text{ (kW)}$$

Therefore, the total electric demand reduction by the DIS cooling system (R) is the sum of R1, R2, and R3.

$$R = R1 + R2 + R3$$

$$= 157.1 \text{ (kW)}$$

Power Consumption Factor in Direct Cooling Mode

From August to November 1988 and again from 1 May to 31 October 1989, the performance of the 220-ton chiller was monitored. The monthly summary for the 1989 cooling season on electrical energy consumed (kWh), cooling output of the chiller (ton-hours) delivered to the Building 506, and power consumption factor (kW/ton) are given below in Table 5. The daily summaries are given in Appendix C.

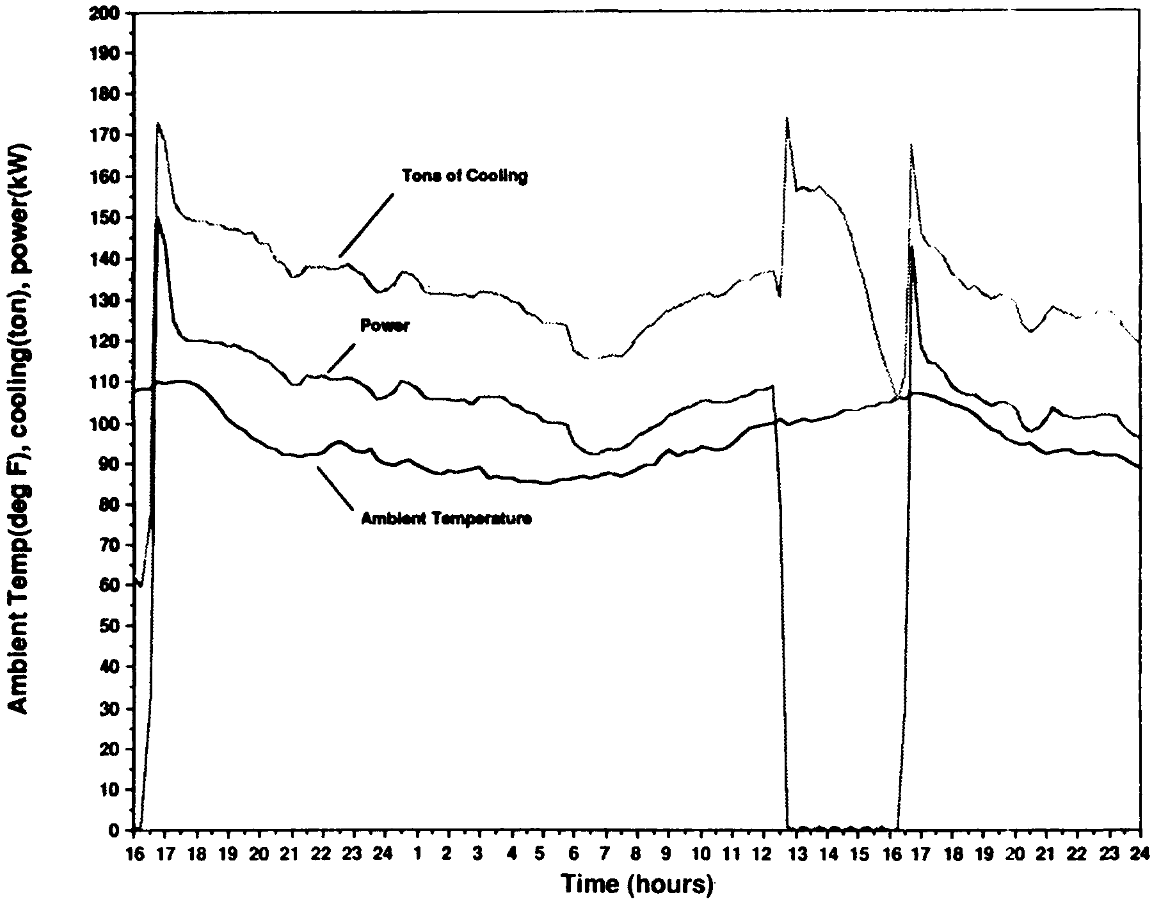


Figure 10. Demand shifting by ice storage.

The seasonal performance of the 220-ton chiller is calculated by dividing the total electrical energy consumed by the total cooling produced. This yields a seasonal PCF of about 0.82. It is interesting to note that the chiller performance is generally higher during the middle of the summer than during the changeover seasons even though the condensing temperature is higher in the summer. This is because of the increased loading factor to the chiller during the summer.

Power Consumption Factor in Storage Cooling Mode

The two aspects of energy performance of all DIS cooling systems are: the efficiency of converting electric energy into storable refrigeration effect (ice making), and the storage efficiency based on the energy stored in the tank and the energy delivered to the load. For the same amount of refrigeration effect (in British thermal units), refrigeration at lower temperature requires more energy[8]. Table 6 shows a monthly summary of the electrical energy (kWh) required for freezing ice, the amount of refrigeration stored in the tank in the form of ice (ton-h), and the amount of cooling delivered to Building 506 from the ice storage tank. The daily summaries are in Appendix D.

[8] C.W. Sohn, G.L. Cler, and R.J. Kedl.

Table 5

Performance of 220-Ton Chiller

Month	Energy Input (kWh)	Cooling Delivered (ton-h)	PCF
May	24,250	30,700	0.79
Jun	41,310	50,010	0.83
Jul	51,580	64,710	0.80
Aug	51,540	65,000	0.79
Sep	41,370	50,590	0.82
Oct	28,360	29,440	0.96
Total	238,410	290,450	0.82

Table 6

Performance of Ice Making Chiller

Month	Energy Input (kWh)	Cooling to Tank (ton-h)	Cooling to Load (ton-h)	PCF
May	40,300	15,040	9617	2.68
Jun	32,350	10,650	8232	3.04
Jul	44,740	15,730	12,043	2.84
Aug	39,050	14,610	12,674	2.67
Sep	45,340	16,970	11,867	2.67
Oct	33,250	13,250	9228	2.51
Total	235,030	86,250	63,661	2.72 (average)

For the 1989 cooling season (May through October), the ice maker required 235,030 kWh of electrical energy. The amount of refrigeration effect delivered to the ice tank during the same period is 86,250 ton-h. Therefore, the PCF during the ice making mode is 2.72 kW/ton.

Energy Performance of Ice Maker

For a comparison to the measured PCF of the ice maker, the prediction of PCF based on the manufacturer's data[9] is presented in the Table 7. The factory rating indicates that the PCF of the unit as an ice maker and as a water cooler, based on the data in Table 7, are 2.1 kW/ton and 1.5 kW/ton, respectively.

In theory, converting the unit into an ice maker results in a 40 percent increase in PCF. This is the energy penalty (0.8 kW/ton vs 2.72 kW/ton) discussed earlier in DIS cooling systems compared to conventional cooling systems. The measured PCF of the ice maker is 2.7 kW/ton for the 1989 cooling season. It is about 28 percent higher than the theoretical PCF expected from the manufacturer's data in Table 7. This is attributed to the unit's age (10 years), and the natural difference between data from a laboratory test and an actual field performance test.

Table 7

Factory Performance Rating of Ice Maker

Ice Making Mode
- Brine entering temperature: 30 °F
- Brine leaving temperature: 25 °F
- Condenser air temperature: 105 °F
- Fouling factor: 0.00050
- Loading: 100 percent
- Total electric power: 103.9 kW
- Cooling tonnage: 49.7 ton

Water Cooling Mode
- Water leaving temperature: 40 °F
- Condenser air temperature: 105 °F
- Fouling factor: 0.00050
- Loading: 100 percent
- Total electric power: 107.3 kW
- Cooling tonnage: 71.7 ton

[9] *Air Cooled Packaged Liquid Chillers, Models LCHA/YCHA*, Product catalog, FORM 150.40-EG1(680) (York Division Borg-Warner, 1980).

The increase in PCF noted above is at least partially corroborated by the Electric Power Research Institute.[10] Results from long term monitoring of several storage systems indicates an average increase in PCF of about 25 percent for the chiller. Using a new chiller for ice production is likely to reduce this value whereas using an older chiller will potentially increase it.

Storage Tank Efficiency

Another important factor in a DIS cooling system is the efficiency of the ice storage tank. The storage tank efficiency, E, is defined by,

E = Cooling delivered from tank/Cooling stored in tank

As shown in Table 6, the ice maker delivered 86,250 ton-h of cooling to the tank during the 1989 cooling season. During the same period, the tank provided 63,660 ton-h of cooling. The numbers include heat contribution from the circulation pumps. During each charging period, a 10-hp circulation pump in the brine loop (see Figure 5) introduces heat into the storage tank. The pump ran 2767 hours during the period of 1 May through 31 Oct 90. Assuming that 90 percent of the electric energy supplied to the circulation pump was converted into heat, the total heat contribution of the circulation pump to the storage tank, H1, is:

H1 = 10 (hp) x 0.75 (kW/hp) x 2767 (h) x 3413 (Btu/kWH)

= 70,828,282 (Btu)

= 5900 (ton-h)

Similarly, the heat contribution from the 7.5-hp circulation pump, H2, between the storage tank and the heat exchanger was absorbed by the storage tank. The pump ran during the discharge period (1200 to 1600 hours) each day for the whole cooling season.

H2 = 7.5 (hp) x 0.75 (kW/hp) x 4 (h/day) x 180 (days) x 3413 (Btu/kWH)

= 13,822,650 (Btu)

= 1150 (ton-h)

The net amounts of cooling delivered to and recovered from the tank during the 1989 cooling season are 80,350 and 64,810 ton-hr, respectively. Therefore, the storage efficiency of the tank is 81 percent.

Again, a theoretical estimate of tank loss was calculated from the following manufacturer's data:

Dimension: 9.5 ft wide x 42 ft long x 7 ft high.
Insulation: Expanded polystyrene insulation 3 in. thick (R-13) on tank sides and ends, and 2 in. thick (R-8) on bottom and top.
Air pump: 42 cu ft/min (for agitator).

[10] Science Applications International Corporation, *Operation and Performance of Commercial Cool Storage Systems: Vols 1 and 2*, EPRI CU-6561 (EPRI, September 1989).

Assume that the average ambient temperature during the 1989 cooling season was 90 °F and the temperature inside the tank remained 30 °F. Heat gain (or cooling loss) through the surface of the tank for 24 hours is calculated by:

$$Q1 = UA(Tout-Tin)t \qquad \text{[Eq 2]}$$

$$= [(1/13)(2x42x7 + 2x9.5x7)+(1/8)(2x9.5x42)]x(90-30)x24$$

$$= 223{,}500 \text{ Btu/day}$$

$$= 19 \text{ ton-h/day}$$

where U = overall heat conductance $\left(\frac{\text{Btu}}{\text{hr °F sq ft}}\right)$
A = area (sq ft).

Heat gain through the air agitation for 24 h would be,

$$Q2 = MC_p(Tout-Tin)t \qquad \text{[Eq 3]}$$

$$= (42x0.071x60)(0.24)(90-30)(24)$$

$$= 61{,}834 \text{ Btu/day}$$

$$= 5 \text{ ton-h/day}$$

where M = air mass flowrate
C_p = specific heat of air.

Heat gain from the 5.5 hp air compressor (with 85 percent compression efficiency) for 24 h would be,

$$Q3 = 5.5 \text{ (hp) x } 0.85 \text{ x } 0.75 \text{ (kW/hp) x } 24 \text{ (hr) x } 3413 \text{ (Btu/kWH)}$$

$$= 287{,}204 \text{ Btu/day}$$

$$= 24 \text{ ton-h/day}$$

Thus, the total heat gain for a day is 48 ton-h.

Note that the storage capacity of the tank is 1000 ton-h. Therefore, the theoretical daily heat gain (or cooling loss) is about 4.8 percent of the tank storage capacity per day. For the entire 1989 cooling season the theoretical heat gain would be 8640 ton-h (48 ton-h/day x 180 days).

The calculated storage efficiency (Et), based on actual stored cooling, would be 89 percent. The discrepancy between the calculated (0.89) and the measured storage efficiency (0.81) would be due to a conservative estimate of the conductive heat gain of the tank. The tank is exposed to solar irradiation; therefore, the average surface temperature of the tank could be higher than the seasonal average air temperature. The effective insulation "R" values of the tank may be lower than the one used in the calculation because of the cold bridges caused by structural steel. This would result in a lower calculated storage efficiency which would agree closely to the measured storage efficiency. The storage efficiency is not only a function of the tank construction but also a strong function of tank operation. This aspect is elaborated in detail in the **Discussion** section.

Economic Performance

The net construction cost for the DIS cooling system for Building 506 was $144,969.00, including the incentive rebate from APS under STEP. A breakdown of the total construction cost is shown in Table 8.

The benefit of the installed system is a reduction in peak electric demand for cooling Building 506. The reduction in demand charge for each kilowatt of power shifted from the peak to offpeak can be calculated by the ratchet factor.[11] Based on the APS emergency demand schedule, the billing demand is the greater of either the actual monthly peak or 80 percent of the highest peak during the immediately preceding 11 months (80 percent ratchet). For the 4 summer months, the actual monthly peak will be the billing demand. For the remaining 8 months, the billing demand will be 80 percent of the yearly peak. Therefore, the annual ratchet factor (F) would be

$$F = 1 \times 4 + 0.8 \times 8$$

$$= 10.4$$

The demand charge is $17.04/kW. Therefore, shifting 1 kW from the peak to offpeak period will result in a cost avoidance (C) of:

$$C = 10.4 \times 17.04$$

$$= \$177.2/\text{kW/yr}$$

The actual peak demand shift measured in the 1989 cooling season was 157.1 kW. The annual peak demand is a function of weather and facility use. Weather variation is difficult to predict. Typically, however, the building cooling load will grow in the future due to increased activities and introduction of more electronic equipment in offices and barracks. A 10 percent increase in cooling load has been assumed to accommodate such a variation in cooling requirement for the period of payback study life. Therefore, the DIS cooling system will shift 173 kW of electric demand from peak to offpeak. The annual savings in demand reduction (R) is

$$R = 177.2\ (\$/\text{kW/yr}) \times 173\ (\text{kW})$$

$$= \$30{,}650/\text{yr}$$

The net saving in electric cost will be less than $30,650/yr due to the extra energy penalty in making ice. Table 6 shows that the DIS cooling system delivered 63,661 ton-h of cooling to the building at the expense of 235,030 kWh. The 220-ton centrifugal chiller could have delivered the same amount of cooling at the PCF of 0.82 kW/ton. Therefore, the energy penalty (P) of the DIS cooling system is

[11] C.W. Sohn and G.L. Cler.

$$P = 235{,}030 - 63{,}660 \times 0.82$$

$$= 182{,}829 \text{ kWh}$$

At the prevailing rate of 0.0451/kWh, the energy penalty cost (D) is

$$D = 182{,}829 \times 0.0451$$

$$= \$8{,}200/\text{yr}$$

The net annual savings in electric cost (S) is

$$S = R - D$$

$$= 30{,}650 - 8{,}200$$

$$= \$22{,}450/\text{yr}$$

Therefore the simple payback period of the system (N) is

N= Net construction cost/net annual savings

$$= 144{,}969/22{,}450$$

$$= 6.5 \text{ yr}$$

If the incentive from APS were not available, the simple payback period would be 8.1 years.

Table 8

Construction Cost Breakdown

Item		Cost
Equipment:	Ice storage tank (BAC Model TSU-1050C)	$60,198
	Heat Exchanger (BAC HIGH-k 10-12-3-1A)	7,836
Equipment Subtotal		68,034
Labor:	Installation labor and miscellaneous parts	114,435
Grand Total		182,469
Incentive:	From Arizona Public Service	37,500
	Net Total	$144,969

Accuracy of Data

The accuracy of the data collected through the data logger was checked against a series of onsite measurements with independent portable instruments. On 4 October 1989, USACERL, ORNL, and APS conducted field measurements of ice maker power consumption and two thermocouple outputs in the brine loop. USACERL and ORNL used their own Esterline-Angus portable kW meters; APS installed a demand recorder for a week (12:57, 11 October to 13:32, 17 October 1989). The outputs of the thermocouples from an ice bath read 32.5 °F, both within 0.1 °F. Although they read 0.5 °F high, the difference between the thermocouples is the most important parameter for load calculations. The variations in this difference is not more than 0.1 °F.

Table 9 shows the measurements of ice maker power consumption with a number of independent instruments at different times.

The USACERL and ORNL meters read instantaneous power readings, whereas the data logger and the APS demand recorder integrate the power for a 15-minute interval and show average power. These measurements confirmed the accuracy of the ice maker power measurements at better than 99 percent.

Discussion

Cost and Energy Efficiency of an Ice Maker

An existing 80-ton reciprocating chiller was converted into an ice maker for the YPG system. The primary reason for using the existing unit was to reduce the system first cost. Admittedly, the unit is not an ideal ice maker for the system; it is more than 10 years old and contains small compressors with air cooled condensers. Even as a water cooler, the factory-predicted power consumption factor of 1.5 kW/ton is rather high (see Table 7). Using the existing chiller eliminated the expense of a new ice maker, which was estimated at $40,000 for this system.

Table 9

Ice Maker Power Consumption Accuracy Test

Date, Time	USACERL	ORNL	APS Recorder	Data Logger
3 Oct, 17:00	103*	103		102
3 Oct, 22:00		97.6		97.8
4 Oct, 08:30		95.8		95.0
11 Oct, 21:00		100.96	100.61	
12 Oct, 19:00			102.56	103.13
16 Oct, 20:00			98.72	98.92
17 Oct, 06:00			91.36	92.11

*All data is in kilowatts.

The savings in first cost may result in unexpectedly high operational costs for the system. The power consumption factor of the ice maker during the 1989 cooling season was measured at 2.7 kW/ton. The ice storage replaces cooling to be provided by an energy efficient chiller whose PCF is 0.8 kW/ton. The energy penalty of the ice storage, compared to the 220-ton chiller, was an extra 182,829 kWh of energy which results in an additional $8200/yr in energy cost and reduces the savings in demand cost by 27 percent. However, it should be noted that the energy penalty in this system is dramatized by: (1) competing against a new 220-ton chiller which is highly efficient in cooling water, and (2) unusual application of an air cooled small reciprocating chiller as an ice maker. For a numerical example, the PCF of the ice maker for an earlier demonstration at Fort Stewart was measured to be 1.39 kW/ton.[12] If the PCF of the YPG ice maker was the same as that at Fort Stewart, the energy penalty would be less than $1600/yr (or 5 percent of the savings due to demand shifting), which is negligible. This provides an important lesson in application of a DIS cooling system especially for a retrofit project using an existing chiller; the energy penalty in making ice with a converted chiller must be fully weighed in calculations of the expected benefit achieved in demand shifting.

Storage Efficiency of the Ice Tank

The storage efficiency of the ice tank measured during the 1989 cooling season was 81 percent, which is lower than expected. A conservative calculated efficiency based on the factory data is 89 percent. In a typical design/operation of a DIS cooling system, the thermal gain by the tank is usually neglected. One of the advantages of an ice storage system over a chilled water storage system is the better storage efficiency. Even for the chilled water storage system, the storage efficiency can reach 90 percent.[13] The storage efficiency of a storage tank depends on the mode of operation and how it is made. As an extreme example, assume that a 1000 ton-h storage tank is fully charged. If the tank stands idle for 20 days, while losing 50 ton-h a day, the storage efficiency of the tank for cooling is 0. However, if the tank is fully discharge during the next day, the storage efficiency is 95 percent.

For the case of YPG, the total seasonal system storage capacity is 180,000 ton-h, and the actual amount of cooling stored was 80,350 ton-h for the 180 days of monitoring. The underutilization of the tank is partly due to oversizing of the storage tank and partly due to an inherent characteristic of the cool storage technology. The oversizing of the tank was caused by the overestimate of the peak cooling load. The design peak cooling load was 209 tons whereas the highest cooling load measured during the 1989 cooling season was 173 tons. The cooling requirement for a typical day is always less than the peak cooling load used in sizing a tank. Therefore, the fully charged tank will never be completely discharged except for the few design days. One method of improving the storage efficiency is a controlled charge/discharge period based on the remaining ice inventory and the next day weather forecast. For the simplicity of control, a fixed charge/discharge period was selected for YPG at the expense of reduced storage efficiency. However, note that the little savings in operational cost through an improved storage efficiency can be easily wiped out by the operation and maintenance cost of a complicated control.

[12] C.W. Sohn and J.J. Tomlinson, "Diurnal Ice Storage Cooling Systems in Army Facilities," *ASHRAE Transactions*, Vol 95, Part 1, (1989).

[13] N. Tran, J.F. Kreider, and P. Brothers, "Field Measurement of Chilled Water Storage Thermal Performance," *ASHRAE Transactions*, Vol 95, Part 3 (1989).

6 CONCLUSION

An ice-on-coil diurnal ice storage cooling system was installed at a barracks/office/dining facility at Yuma Proving Ground, AZ to reduce peak electrical demand by 200 kW. This installation was unique in that the building had two operating chillers: a 209-ton centrifugal chiller and an 80-ton air cooled, reciprocating chiller. The system was designed as a retrofitted "add-on." Because the 80-ton unit was available on site, it was modified and converted to an ice maker which saved in the cost of buying an ice maker. The storage unit was to provide cooling between 1200 and 1600 hours.

To cut the system construction costs, the Government procured the equipment (for $68,034) and contracted the installation (for $114,435). The cooling capability was not compromised during construction. During preliminary performance testing, the air blower for the ice storage tank failed. The manufacturer provided a new blower as covered by the warranty. Two of the four small compressors in the ice maker (80-ton chiller) were replaced when normal ice production decreased significantly.

Thermocouples, flowmeters, and watt/watt-hour meters collected operational data from 1 May through 31 October 1989. Based on this data, the total electric demand reduction due to the DIS system was 157.1 kW. The savings in electricity ($30,650/yr) was reduced by the cost of the extra energy used to make ice ($8200) to yield a net annual savings of $22,450. An incentive payment from Arizona Public Service reduced the system's grand total to $144,969. Therefore, the simple payback period for the system is 6.5 years.

The salient features of the project are listed below.

Project Administration

- Project Management: USACERL
- System Design: ORNL
- Contract Award and Construction Supervision: YPG
- Construction Contractor: AT Mechanical
- Construction Cost:
  - Equipment: $68,034
  - Labor: $114,435
  - Grand Total: $182,469
  - Incentive Award from APS: $37,500
  - Net System Construction Cost: $144,969

Design Characteristics

- System Application: Retrofit
- Floor area of Building 506: 86,100 sq ft
- Type of Facility: Barracks/Offices/Dining Hall
- Chiller Shut-off Window: 1200 to 1600
- Design Tank Capacity: 900 ton-h
- Nominal Tank Capacity: 1050 ton-h
- Tank Installed: One tank, BAC Model TSU-1050C
- Type of Tank: Ice-on-coil
- Charging Time: maximum 20 h
- Brine: 30 percent ethylene glycol
- Entering Brine Temperature: 25 °F
- Temperature Rise: 5 degrees
- Ice Maker:
  - Unit: YORK Model LCHA-85-46C
  - Nominal Capacity as Water Cooler: 85 ton

Ice Making Capacity as Ice Maker: 45 ton
Chiller:
Unit: Trane, CENTRAVAC
Nominal Capacity: 220 ton

METRIC CONVERSION TABLE

1 gal	=	3.78 L
1 sq ft	=	0.028 m^2
1 in.	=	2.54 cm
°C	=	0.55 (°F - 32)
1kWh	=	3.6 MJ

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APPENDIX A:

EMERGENCY POWER SUPPLEMENT

PURCHASE OF ADDITIONAL EMERGENCY POWER
(Refer APS Contract No. 8307)

DEMAND:	
Maximum Scheduled Demand:	950 kW
Maximum Contract Demand:	750 kW
Excess Demand:	200 kW
ENERGY:	
Scheduled Excess Energy =	23,000 kWh
50 Percent Load Factor of 200 kW =	74,400 KWh
Billing Energy:	74,400 KWh
BILLING COMPUTATIONS:	
Demand Charge: 200 kW @ $17.08/kW =	$3,416.00
Energy Charge: 74,400 kWh @ $0.04511/kWh =	$3,356.18
Fuel Adjustment: 74,400 kWh @ $0.000000/kWh =	$ 0
SUBTOTAL	6,772.18
State Tax and Regulatory Assessment @ 4.1105 percent =	$ 277.69
TOTAL DUE FOR EXCESS EMERGENCY POWER:	$7,049.87

APPENDIX B:

EXAMPLE RATE SCHEDULE FOR CONTRACT POWER

A. P. S. POWER CONTRACT BILLING

STATEMENT OF ACCOUNT FOR SERVICE RENDERED BY
ARIZONA PUBLIC SERVICE COMPANY

FACILITIES ENGINEER DIRECTORATE
U.S. ARMY, YUMA PROVING GROUND
P. O. BOX 3278
YUMA, ARIZONA 85364

PHOENIX, ARIZONA 09-Sep-85
INV. # 509 45000159
ACCT. NO. 1142-001-20059

SERVICE FOR: AUGUST, 1985

DEMAND:
SCHEDULED DEMAND: 500 KW
BILLING DEMAND: 500 KW

ENERGY:
SCHEDULED: 185,960 KWH
BILLING ENERGY/CONTRACT: ~~186,000 KWH~~

RATE E-32

BASIC SERVICE CHARGE:				$12.50
DEMAND CHARGE:	500 - 5 KW =		495 @ $1.50/KW	$742.50
	2,500 KWH			
100 KWH X 495	49,500 KWH			
	52,000 KWH	@ $0.09390/KWH =		$4,882.80
	42,000 KWH	@ $0.06570/KWH =		$2,759.40
	92,000 KWH	@ $0.04300/KWH =		$3,956.00
	186,000			$12,353.20
FUEL ADJUSTMENT:	186,000 KWH	@ $0.000000 /KWH =		$0.00
SUBTOTAL:				$12,353.20

$/KWH=$0.0697955

BILLING AMOUNT:				$12,353.20
REGULATORY ASSESSMENT:	@	0.0857%	.0008	$10.59
SUBTOTAL:				$12,363.79
STATE TAX:	@	5.0%	.05	$618.19
TOTAL DUE:				$12,981.98

TERMS: PAYMENT IS DUE AND PAYABLE SEPTEMBER 19, 1985 IF PAYMENT IS NOT RECEIVED ON OR BEFORE THE DUE DATE, INTEREST WILL BE COMPUTED IN ACCORDANCE WITH THE LATE PAYMENT PROVISIONS OF THE POWER AGREEMENT

REMIT TO: ARIZONA PUBLIC SERVICE CO.
ATTN. : FINANCIAL SERVICES STA. 1820
P. O. BOX 21666
PHOENIX, AZ 85036

CJH

APPENDIX C:

DAILY PERFORMANCE SUMMARIES (220-TON CHILLER)

MAY 1989 — 220 ton chiller

day	Tamb max	Tin max	off pk t-h	off pk ton	on peak t-h	on peak ton	off pk kWh	off pk kW	on peak kWh	on peak kW	offpk FCF
1	96	81	1040	108	273	85	923	73	2	1	0.89
2	101	81	835	141	674	103	758	67	5	1	0.91
3	103	78	839	152	395	109	424	150	2	1	0.51
4	102	77	1119	162	379	109	789	151	2	1	0.71
5	104	77	1109	158	375	111	798	149	2	1	0.72
6	105	76	1331	153	374	113	973	149	2	1	0.73
7	108	76	1391	164	374	113	1057	150	2	1	0.76
10	105	78	1140	154	667	113	829	149	5	1	0.75
11	90	76	431	127	227	66	216	131	2	1	0.50
12	85	78	323	141	261	75	112	64	2	1	0.35
13	86	79	589	144	307	79	375	149	2	1	0.64
14	88	81	468	156	284	79	235	150	2	1	0.50
15	87	80	495	161	288	81	305	116	2	1	0.62
16	89	81	710	146	327	84	659	148	2	1	0.93
17	96	81	896	114	336	91	684	147	2	1	0.76
18	97	82	1258	115	353	92	1019	110	2	1	0.81
19	103	83	1118	138	349	96	894	148	3	1	0.80
20	106	83	1334	119	369	103	1061	148	3	1	0.80
21	108	84	1574	164	370	105	1211	149	2	1	0.77
23	106	83	1281	130	793	129	968	82	90	102	0.76
24	105	82	1632	120	412	106	1347	93	75	92	0.83
25	101	84	1461	110	386	129	1263	85	264	85	0.86
26	103	85	1447	115	450	111	1275	82	350	87	0.88
27	103	75	1498	113	420	108	1283	85	2	1	0.86
28	101	71	1757	108	398	106	1406	92	60	89	0.80
29	103	71	1369	113	334	101	1245	82	22	82	0.91
30	101	76	991	112	368	108	951	148	77	82	0.96
31	97	73	1268	122	407	114	1192	149	67	86	0.94
max	108	85		164		129		151		102	
avg	99	79		134		101		121		26	0.74
total/1000			30.70		10.9[illegible]		24.25		1.053		

JUN 1989 220 ton chiller

day	Tamb max	Tin max	off peak t-h	off peak ton	on peak t-h	on peak ton	off peak kWh	off peak kW	on peak kWh	on peak kW	off pk PCF
1	104	71	1353	125	429	108	1255	83	63	86	0.93
2	104	78	1404	109	400	108	1307	85	76	93	0.93
3	105	78	1428	119	429	109	1310	83	2	1	0.92
4	105	78	1490	115	409	120	1350	98	2	1	0.91
5	104	78	1446	119	354	100	1323	110	2	1	0.91
6	101	78	1441	141	386	110	1323	143	69	99	0.92
7	104	78	1671	130	405	107	1459	84	323	85	0.87
8	106	78	1501	108	392	102	1375	85	319	83	0.92
9	105	78	1505	116	438	115	1348	83	73	88	0.90
10	104	78	1803	112	437	114	1532	89	2	1	0.85
11	104	78	1504	122	455	115	1352	95	2	1	0.90
12	105	79	1596	114	454	124	1395	89	2	1	0.87
13	109	79	1671	119	491	128	1449	96	73	90	0.87
14	111	79	1766	124	513	135	1499	101	83	93	0.85
15	113	82	1131	158	522	167	327	148	419	121	0.29
16	113	79	2179	134	492	129	1768	106	391	103	0.81
17	114	79	2088	130	494	128	1702	103	384	100	0.82
18	116	79	1846	127	523	132	1554	100	409	105	0.84
19	115	79	2170	134	466	127	1742	106	165	95	0.80
20	113	79	2244	125	519	154	1848	103	74	102	0.82
21	115	79	2186	135	500	132	1688	113	72	96	0.77
22	109	82	1403	143	509	129	498	149	390	100	0.35
23	115	80	1868	132	497	142	1887	156	117	93	1.01
24	107	79	1955	116	481	150	1662	95	21	1	0.85
25	105	82	758	112	481	150	249	91	21	1	0.33
26	108	86	461	109	929	150	247	91	383	94	0.54
27	110	88	1969	118	448	116	1662	96	369	97	0.84
28	109	84	2151	116	464	117	1845	100	397	101	0.86
29	110	84	2017	118	519	140	1694	100	2	1	0.84
30	112	84	2013	146	474	132	1660	99	340	100	0.82
max	116	88		158		167		156		121	
avg	109	80		124		126		103		68	0.83
total/1000			50.01		14.31		41.31		5.045		

JUL 1989 — 220 ton chiller

day	Tamb max	Tin max	off peak t-h	off peak ton	on peak t-h	on peak ton	off peak kWh	off peak kW	on peak kWh	on peak kW	off pk PCF
1	113	84	1914	120	389	112	1608	100	324	90	0.84
2	113	84	1983	114	458	116	1678	95	387	99	0.85
3	115	84	1944	117	436	124	1672	98	3	1	0.86
4	117	84	2083	142	490	134	1723	99	2	1	0.83
5	117	84	1809	124	842	146	1542	111	380	122	0.85
6	115	79	2424	148	538	140	1916	114	261	111	0.79
7	116	79	2371	140	593	161	1930	113	30	111	0.81
8	116	79	2300	131	530	136	1865	107	428	110	0.81
9	111	78	2039	133	486	126	1731	107	394	102	0.85
10	109	78	2250	136	521	138	1817	100	27	98	0.81
11	111	78	2110	134	610	139	1695	102	180	120	0.80
12	111	79	2243	155	526	139	1800	104	2	1	0.80
13	115	79	2087	141	470	135	1666	100	5	101	0.80
14	116	79	2129	146	530	134	1687	100	2	1	0.79
15	115	78	2480	150	560	157	1980	109	2	1	0.80
16	110	78	2199	143	515	132	1754	104	2	1	0.80
17	112	78	2145	124	527	143	1714	101	2	1	0.80
18	113	79	2062	136	522	132	1633	98	2	1	0.79
19	115	79	2240	149	546	141	1776	102	5	114	0.79
20	115	79	2235	156	558	143	1780	113	2	1	0.80
21	117	78	2501	148	568	156	2005	119	2	1	0.80
22	112	85	1060	169	1028	150	188	150	464	121	0.18
23	115	79	2557	143	529	166	2033	121	57	111	0.80
24	113	79	2515	162	531	154	2010	145	51	117	0.80
25	117	79	2225	141	571	154	1739	107	54	104	0.78
26	114	79	2529	147	627	173	1990	119	61	119	0.79
27	113	78	2616	149	602	163	2060	123	56	109	0.79
28	107	86	776	146	865	163	673	121	59	109	0.87
29	107	86	1562	168	474	150	1001	151	338	93	0.64
30	107	78	1889	106	437	150	1651	91	309	93	0.87
31	109	78	1441	97	835	150	1267	85	643	93	0.88
max	117	86		169		173		151		122	
avg	113	80		139		144		110		73	0.80
total/1000			64.71		17.71		51.58		4.534		

AUG 1989 — 220 ton chiller

day	Tamb max	Tin max	off peak t-h	off peak ton	on peak t-h	on peak ton	off peak kWh	off peak kW	on peak kWh	on peak kW	off pk PCF
1	109	79	2228	134	505	130	1788	107	403	104	0.80
2	112	79	2538	140	559	171	2053	113	154	112	0.81
3	108	79	2432	131	540	165	1981	106	158	110	0.81
4	109	78	2497	135	568	165	2035	109	48	104	0.81
5	110	79	2591	141	590	168	2053	112	51	108	0.79
6	107	79	2508	141	592	170	1996	113	51	110	0.80
7	108	79	2549	141	579	169	2023	113	50	107	0.79
8	109	83	1886	142	595	210	1490	115	8	1	0.79
9	109	79	2555	152	516	147	1807	121	2	1	0.71
10	109	79	2027	165	1131	163	1594	148	63	112	0.79
11	100	78	2471	149	580	155	1967	121	54	99	0.80
12	107	78	2470	141	587	176	1967	123	49	109	0.80
13	110	79	2546	139	578	180	2031	113	51	113	0.80
14	110	79	2487	136	543	138	1977	106	436	111	0.79
15	111	79	2535	145	638	182	2032	116	51	115	0.80
16	110	79	2663	158	382	139	1864	117	2	1	0.70
17	110	80	2645	173	573	174	2110	150	49	110	0.80
18	107	78	2356	168	590	155	1862	148	42	93	0.79
19	108	78	2112	128	537	155	1666	102	42	94	0.79
20	107	79	2186	132	491	147	1722	98	40	90	0.79
21	107	78	1936	117	429	112	1543	91	340	88	0.80
22	104	78	1901	112	483	138	1558	87	37	82	0.82
23	106	79	1897	126	483	138	1518	93	37	82	0.80
25	104	77	0	0	239	121	0	0	1	1	----
26	107	78	1795	117	457	132	1475	89	36	80	0.82
27	107	78	1510	113	441	133	1316	86	36	79	0.87
28	110	79	1707	118	434	112	1440	94	346	89	0.84
29	112	78	1730	114	464	141	1488	90	39	86	0.86
30	114	79	2015	133	471	130	1410	95	2	1	0.70
31	111	79	2224	132	558	160	1775	106	47	105	0.80
max	114	83		173		210		150		115	
avg	108	79		132		153		106		83	0.79
total/1000			65.00		16.13		51.54		2.73		

SEP 1989 220 ton chiller

day	Tamb max	Tin max	off peak t-h	off peak ton	on peak t-h	on peak ton	off peak kWh	off peak kW	on peak kWh	on peak kW	off pk PCF
1	107	78	1270	119	522	150	1041	97	43	96	0.82
2	108	79	2448	133	589	169	1944	108	48	106	0.79
3	109	78	2285	141	562	160	1813	102	44	99	0.79
4	109	79	2313	140	496	127	1838	102	393	100	0.79
5	114	79	2168	122	625	154	1762	97	116	99	0.81
6	117	79	2371	146	508	138	1665	104	2	1	0.70
7	109	79	2149	138	521	150	1728	122	40	88	0.80
8	108	79	1812	131	531	133	1452	95	36	79	0.80
9	104	79	1725	116	445	127	1427	86	35	77	0.83
10	104	78	1560	145	421	126	1301	149	35	78	0.93
11	105	78	1600	127	452	116	1198	84	2	1	0.75
12	106	78	1665	105	453	132	1416	87	37	82	0.85
13	104	78	1713	117	442	117	1265	87	2	1	0.74
14	105	78	1591	104	428	127	1368	82	36	78	0.86
15	105	77	1585	108	441	119	1346	82	34	73	0.85
16	106	77	1767	107	432	132	1465	84	37	82	0.83
17	107	78	1984	110	467	129	1632	91	41	90	0.82
18	97	79	1059	139	432	117	794	148	3	1	0.75
19	94	78	1185	153	329	100	1079	109	31	67	0.91
20	89	77	837	119	321	83	659	148	2	1	0.79
21	100	77	1222	80	360	108	1173	74	31	67	0.96
22	108	78	1377	89	375	110	1246	78	31	68	0.90
23	109	77	1474	92	409	122	1303	80	35	76	0.88
24	108	77	1553	103	451	131	1349	83	37	83	0.87
25	107	77	1904	139	459	120	1376	91	2	1	0.72
26	108	77	1934	120	439	135	1613	104	38	84	0.83
27	108	77	1606	109	396	102	1217	86	2	1	0.76
28	107	77	1515	99	393	115	1323	83	32	71	0.87
29	108	77	1448	98	374	110	1283	81	31	66	0.89
30	104	77	1466	96	363	109	1296	79	31	67	0.88
max	117	79		153		169		149		106	
avg	106	78		118		126		97		63	0.82
total/1000			50.59		13.44		41.37		1.29		

OCT 1989 220 ton chiller

day	Tamb max	Tin max	off peak t-h	off peak ton	on peak t-h	on peak ton	off peak kWh	off peak kW	on peak kWh	on peak kW	off pk PCF
1	103	77	1354	91	364	108	1237	76	30	66	0.91
2	101	77	1481	94	309	79	1167	76	2	1	0.79
3	95	77	1245	80	321	95	1197	71	18	59	0.96
4	94	78	1230	91	313	85	1133	74	3	1	0.92
5	94	77	1422	107	343	90	1241	75	2	1	0.87
6	97	77	1474	116	384	99	1262	72	2	1	0.86
7	95	77	1359	100	342	87	1205	75	2	1	0.89
8	97	77	1235	96	325	84	1134	71	3	1	0.92
9	99	77	1224	96	320	83	1130	75	2	1	0.92
10	103	77	1211	95	325	85	1126	73	2	1	0.93
11	104	77	1242	95	306	104	1137	76	161	70	0.92
12	100	77	1245	83	345	103	1182	74	31	67	0.95
13	100	77	1249	87	340	123	1189	77	30	65	0.95
14	101	77	1230	91	343	111	1174	75	33	72	0.95
15	94	77	622	156	309	98	619	126	30	65	1.00
16	93	77	789	114	307	97	772	148	29	63	0.98
17	95	77	1094	80	375	110	1113	72	32	69	1.02
18	96	77	1075	105	377	114	1032	149	33	73	0.96
19	96	77	1037	72	358	129	1072	74	27	60	1.03
20	92	77	1083	91	401	133	1069	68	28	61	0.99
21	93	77	1069	93	345	126	1077	75	26	58	1.01
22	90	77	978	89	365	131	1041	61	28	60	1.06
23	91	77	1046	69	374	124	1068	61	28	61	1.02
24	90	77	726	87	348	111	754	149	27	60	1.04
25	89	76	722	89	268	120	802	149	27	57	1.11
26	75	76	72	112	252	103	125	155	25	53	1.74
27	80	75	200	92	312	112	249	152	25	52	1.25
28	83	75	228	85	264	100	318	149	25	54	1.39
29	79	75	233	85	238	103	334	152	19	45	1.43
30	74	74	136	82	223	91	199	125	24	51	1.46
31	79	75	124	102	243	97	199	76	23	48	1.60
max	104	78		156		133		155		73	
avg	93	77		94		104		96		45	0.96
total/1000			29.44		10.04		28.36		0.78		

APPENDIX D:

DAILY PERFORMANCE SUMMARIES (80-TON CHILLER)

MAY 1989 — 80 ton chiller

day	Tamb max	off pk t-h	off pk ton	on peak t-h	on peak ton	off pk kWh	off pk kW	on peak kWh	on peak kW	offpk PCF
1	96	516	34	0	0	1452	99	3	1	2.81
2	101	434	33	0	0	1181	92	5	1	2.72
3	103	566	39	0	0	1519	108	3	1	2.68
4	102	631	46	0	0	1593	115	3	1	2.52
5	104	649	49	0	0	1606	118	3	1	2.47
6	105	651	50	0	0	1613	118	3	1	2.48
7	108	647	50	0	0	1597	119	3	1	2.47
10	105	505	45	0	0	1268	104	5	1	2.51
11	90	660	50	0	0	1444	105	3	1	2.19
12	85	615	45	0	0	1404	97	3	1	2.28
13	86	610	44	0	0	1449	101	3	1	2.38
14	88	613	44	0	0	1442	103	3	1	2.35
15	87	615	44	0	0	1444	102	3	1	2.35
16	89	628	38	0	0	1604	97	3	1	2.55
17	96	556	38	0	0	1462	99	3	1	2.63
18	97	590	40	0	0	1514	107	3	1	2.57
19	103	603	43	0	0	1559	112	3	1	2.59
20	106	602	44	0	0	1598	116	3	1	2.65
21	108	600	47	0	0	1562	115	3	1	[illegible].60
23	106	473	43	19	0	1295	99	103	114	2.74
24	105	609	35	8	0	1779	112	62	105	[illegible].92
25	101	51	40	90	0	180	109	297	118	[illegible].53
26	103	454	26	81	0	1476	99	342	93	[illegible].25
27	103	403	24	0	0	1393	80	3	1	3.46
28	101	391	24	10	0	1390	108	62	93	3.55
29	103	438	25	6	0	1458	93	24	93	[illegible].33
30	101	490	29	22	0	1525	112	81	93	3.11
31	97	441	24	9	0	1499	110	71	105	3.40
max	108		50		0		119		118	
avg	99		39		0		105		30	[illegible].68
total/1000		15.04		0.245		40.30		1.106		

JUN 1989 80 ton chiller

day	Tamb max	off peak t-h	off peak ton	on peak t-h	on peak ton'	off peak kWh	off peak kW	on peak kWh	on peak kW	off pk PCF
1	104	406	24	9	0	1444	91	72	105	3.56
2	104	420	23	14	0	1475	86	79	84	3.51
3	105	409	23	0	0	1471	83	3	1	3.60
4	105	421	24	0	0	1523	92	3	1	3.62
5	104	381	23	0	0	1067	73	3	1	2.80
6	101	417	25	13	0	1100	75	48	53	2.64
7	104	386	23	105	0	1060	101	380	101	2.75
8	106	559	32	106	0	1721	101	387	99	3.08
9	105	312	29	0	0	1031	99	3	1	3.30
10	104	0	0	0	0	14	1	3	1	----
11	104	560	31	0	0	1784	100	3	1	3.19
12	105	559	31	0	0	1776	102	3	1	3.18
13	109	547	30	20	0	1821	102	79	97	3.33
14	111	533	30	21	0	1841	102	90	100	3.45
15	113	51	26	69	0	172	122	195	76	3.37
16	113	561	37	112	0	1353	112	363	110	2.41
17	114	738	40	125	0	2018	109	428	108	2.73
18	116	136	34	0	0	461	108	3	1	3.39
19	115	0	0	0	0	13	1	3	1	----
20	113	62	36	0	0	231	103	3	1	3.73
21	115	681	40	24	0	1920	111	86	108	2.82
22	109	244	84	110	0	504	149	270	139	2.07
23	115	770	45	25	0	1986	132	106	105	2.58
24	107	328	18	3	0	1079	57	14	1	3.29
25	105	43	17	3	0	165	57	14	1	3.84
26	108	43	17	81	0	162	57	274	66	3.77
27	110	340	19	120	0	1132	64	417	107	3.33
28	109	742	41	133	0	1990	109	416	105	2.68
29	110	5	22	0	0	30	1	3	1	6.00
30	112	0	0	42	0	14	1	216	62	----
max	116		84		0		149		139	
avg	109		27		0		83		55	3.04
total/1000		10.65		1.135		32.35		3.967		

JUL 1989 80 ton chiller

day	Tamb max	off peak t-h	off peak ton	on peak t-h	on peak ton	off peak kWh	off peak kW	on peak kWh	on peak kW	off pk PCF
1	113	247	17	0	0	375	59	3	1	3.54
2	113	92	18	22	0	360	58	130	108	3.91
3	115	60	18	0	0	276	108	3	1	4.60
4	117	298	17	0	0	1101	65	3	1	3.69
5	117	316	25	50	0	940	71	207	59	2.97
6	115	362	34	71	0	1260	108	252	114	3.48
7	116	710	39	8	0	2024	112	30	111	2.85
8	116	705	40	61	0	2034	113	204	108	2.89
9	111	0	0	0	0	14	1	3	1	----
10	109	12	35	0	0	74	103	3	1	6.17
11	111	129	40	51	0	385	105	180	125	2.98
12	111	762	42	0	0	2027	119	3	1	2.66
13	115	709	40	-12	0	2013	115	5	42	2.84
14	116	659	39	0	0	2064	111	3	1	3.13
15	115	689	39	0	0	2028	117	3	1	2.94
16	110	718	40	0	0	2009	113	3	1	2.80
17	112	703	40	0	0	1999	121	3	1	2.84
18	113	700	40	0	0	2011	112	3	1	2.87
19	115	660	38	-12	0	2026	113	4	42	3.07
20	115	680	37	0	0	2020	113	3	1	2.97
21	117	682	38	0	0	2031	117	3	1	2.98
22	112	10	23	100	0	45	162	195	84	4.50
23	115	814	56	17	0	1821	118	56	107	2.24
24	113	734	55	11	0	1911	146	39	107	2.60
25	117	712	43	16	0	1976	124	56	107	2.78
26	114	729	40	17	0	2007	121	55	107	2.75
27	113	717	40	17	0	2025	121	55	107	2.82
28	107	322	45	17	0	905	116	58	107	2.81
29	107	597	82	135	0	1278	140	393	108	2.14
30	107	747	40	122	0	2013	106	365	107	2.69
31	109	455	40	122	0	1194	103	367	107	2.62
max	117		82		0		162		125	
avg	113		37		0		107		57	2.84
total/1000		15.73		0.813		44.74		2.69		

AUG 1989 30 ton chiller

day	Tamb max	off peak t-h	off peak ton	on peak t-h	on peak ton	off peak kWh	off peak kW	on peak kWh	on peak kW	off pk PCF
1	109	-3	0	39	0	14	1	138	106	-4.67
2	112	11	37	-1	0	78	101	3	1	7.09
3	108	24	37	26	0	118	103	115	114	4.92
4	109	742	41	15	0	2032	109	49	103	2.74
5	110	725	41	16	0	1957	108	48	103	2.70
6	107	723	40	15	0	1955	109	48	101	2.70
7	108	727	40	15	0	1944	110	49	104	2.67
8	109	522	39	-5	0	1520	109	4	1	2.91
9	109	664	42	0	0	1757	121	3	1	2.65
10	109	640	51	20	0	1493	111	57	99	2.33
11	100	814	52	20	0	1909	111	55	100	2.35
12	107	649	41	15	0	1698	107	46	103	2.62
13	110	733	41	14	0	1970	113	47	106	2.69
14	110	706	40	132	0	1985	111	421	106	2.81
15	111	238	37	0	0	771	106	3	1	3.24
16	110	0	0	0	0	14	1	3	1	----
17	110	813	61	15	0	2044	136	48	104	2.51
18	107	742	50	15	0	2010	130	48	105	2.71
19	108	741	42	15	0	1974	119	47	102	2.66
20	107	737	41	16	0	1955	111	46	101	2.65
21	107	738	41	74	0	1929	108	212	103	2.61
22	104	17	41	0	0	76	100	3	1	4.47
23	106	17	41	0	0	76	100	3	1	4.47
25	104	0	0	0	0	0	0	1	1	----
26	107	738	42	15	0	1924	108	46	102	2.61
27	107	29	35	0	0	134	107	3	1	4.62
28	110	761	42	135	0	1945	117	415	108	2.56
29	112	201	36	0	0	600	104	3	1	2.99
30	114	418	40	0	0	1212	110	3	1	2.90
31	111	738	41	10	0	1957	120	33	84	2.65
max	114		61		0		136		114	
avg	108		38		0		100		66	2.67
total/1000		14.61		0.62		39.05		2.00		

SEP 1989 — 30 ton chiller

day	Tamb max	off peak t-h	off peak ton	on peak t-h	on peak ton	off peak kWh	off peak kW	on peak kWh	on peak kW	off pk PCF
1	107	448	41	15	0	1159	106	47	102	2.59
2	108	700	39	14	0	1969	109	47	104	2.81
3	109	710	40	14	0	1955	110	47	102	2.75
4	109	559	39	0	0	1565	110	3	1	2.80
5	114	70	39	13	0	259	111	50	108	3.70
6	117	632	39	0	0	1787	115	3	1	2.83
7	109	737	44	15	0	1981	122	47	106	2.69
8	108	714	41	15	0	1920	110	47	105	2.69
9	104	661	42	0	0	1688	107	3	1	2.55
10	104	391	41	0	0	1051	107	3	1	2.69
11	105	586	42	0	0	1462	108	3	1	2.49
12	106	757	41	15	0	1934	117	46	101	2.55
13	104	659	40	0	0	1754	107	3	1	2.66
14	105	738	41	15	0	1946	111	46	101	2.64
15	105	635	41	0	0	1711	107	3	1	2.69
16	106	40	38	0	0	156	104	3	1	3.90
17	107	725	41	16	0	1981	121	45	100	2.73
18	97	695	42	0	0	1670	106	3	1	2.40
19	94	788	44	0	0	1829	105	3	1	2.32
20	89	278	46	0	0	685	98	3	1	2.46
21	100	775	43	15	0	1898	104	45	101	2.45
22	108	0	0	0	0	14	1	3	1	ERR
23	109	735	43	14	0	1970	115	48	105	2.68
24	108	509	40	-2	0	1445	109	21	40	2.84
25	107	501	38	0	0	1430	107	3	1	2.85
26	108	714	41	14	0	2008	122	48	106	2.81
27	108	649	41	0	0	1774	111	3	1	2.73
28	107	715	42	14	0	1966	112	48	105	2.75
29	108	514	41	0	0	1409	110	3	1	2.74
30	104	335	39	0	0	968	107	3	1	2.89
max	117		46		0		122		108	
avg	106		40		0		106		47	2.67
total/1000		16.97		0.19		45.34		0.68		

OCT 1989 80 ton chiller

day	Tamb	off peak		on peak		off peak		on peak		off pk
	max	t-h	ton	t-h	ton	kWh	kW	kWh	kW	PCF
1	103	518	42	0	0	1356	108	3	1	2.62
2	101	208	41	0	0	631	107	3	1	3.03
3	95	805	45	9	0	1905	113	27	98	2.37
4	94	537	41	0	0	1344	103	3	1	2.50
5	94	329	42	0	0	893	104	3	1	2.71
6	97	653	42	0	0	1599	106	3	1	2.45
7	95	459	41	0	0	1188	105	3	1	2.59
8	97	533	42	0	0	1372	106	3	1	2.57
9	99	388	42	0	0	1014	106	3	1	2.61
10	103	699	43	0	0	1733	109	3	1	2.48
11	104	319	43	38	0	917	107	137	110	2.87
12	100	122	41	0	0	390	102	3	1	3.20
13	100	724	41	0	0	1850	108	3	1	2.56
14	101	222	40	0	0	636	106	3	1	2.86
15	94	442	44	0	0	1063	104	3	1	2.40
16	93	225	46	0	0	612	101	3	1	2.72
17	95	648	43	0	0	1525	104	3	1	2.35
18	96	294	43	0	0	847	105	3	1	2.88
19	96	528	43	0	0	1343	107	3	1	2.54
20	92	327	42	0	0	930	105	3	1	2.84
21	93	680	42	0	0	1733	106	3	1	2.55
22	90	182	42	-3	0	473	101	9	1	2.60
23	91	769	43	0	0	1823	105	3	1	2.37
24	90	306	41	17	0	792	102	44	99	2.59
25	89	413	43	0	0	1025	103	3	1	2.48
26	75	131	44	0	0	310	96	3	1	2.37
27	80	609	47	0	0	1255	101	3	1	2.06
28	83	176	43	0	0	433	98	3	1	2.46
29	79	427	44	0	0	977	100	3	1	2.29
30	74	156	44	0	0	371	96	3	1	2.38
31	79	417	45	0	0	911	98	3	1	2.18
max	104		47		0		113		110	
avg	93		43		0		104		11	2.51
total/1000		13.25		0.06		33.25		0.30		

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